Advanced Low Conductivity Thermal Barrier Coatings: Performance and Future Directions (Invited paper)

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Thermal barrier coatings will be more aggressively designed to protect gas turbine engine hot-section components in order to meet future engine higher fuel efficiency and lower emission goals. In this presentation, thermal barrier coating development considerations and performance will be emphasized. Advanced thermal barrier coatings have been developed using a multi-component defect clustering approach, and shown to have improved thermal stability and lower conductivity. The coating systems have been demonstrated for high temperature combustor applications. For thermal barrier coatings designed for turbine airfoil applications, further improved erosion and impact resistance are crucial for engine performance and durability. Erosion resistant thermal barrier coatings are being developed, with a current emphasis on the toughness improvements using a combined rare earth- and transition metal-oxide doping approach. The performance of the toughened thermal barrier coatings has been evaluated in burner rig and laser heat-flux rig simulated engine erosion and thermal gradient environments. The results have shown that the coating composition optimizations can effectively improve the erosion and impact resistance of the coating systems, while maintaining low thermal conductivity and cyclic durability. The erosion, impact and high heat-flux damage mechanisms of the thermal barrier coatings will also be described.

Advanced Low Conductivity Thermal Barrier Coatings: Performance and Future Directions

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35th International Conference On Metallurgical Coatings And Thin Films (ICMCTF 2008)
San Diego, California, April 27-May 2, 2008

Acknowledgments

This work was supported by NASA Fundamental Aeronautics (FA) Program Supersonics and Subsonic Rotary Wing Projects.

Collaborators

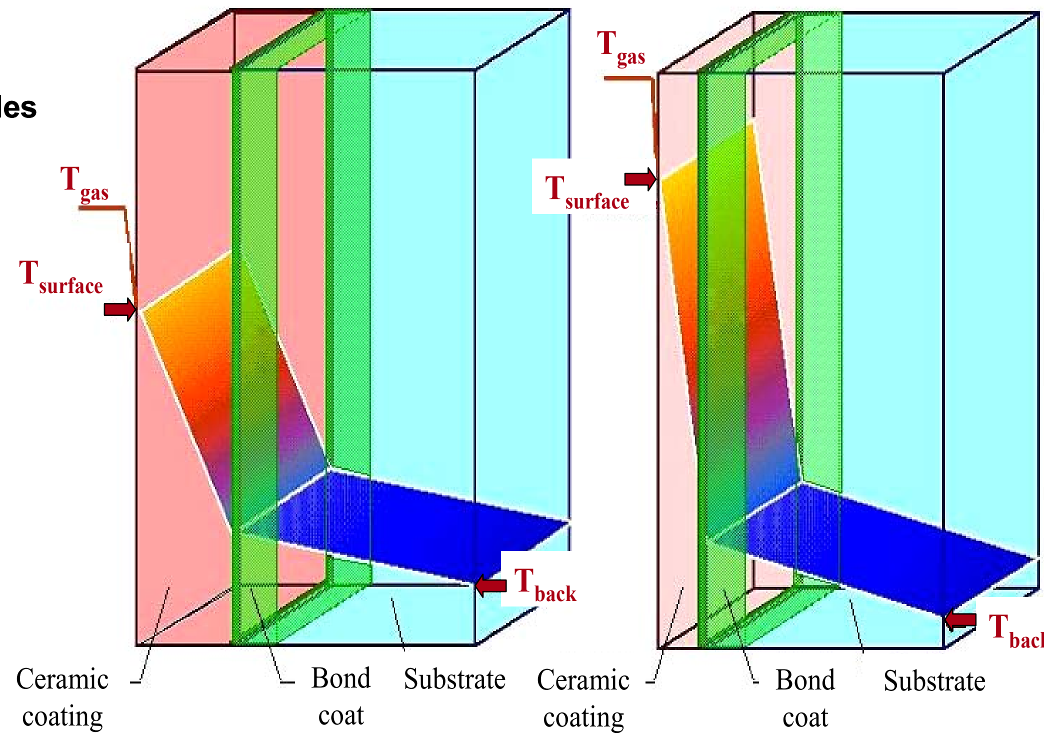
GE Aviation	Howmet Coatings
Pratt and Whitney	Honeywell Engines
Rolls Royce-Liberty Works	UCSB
SUNY/Mesoscibe Tech.	Direct Vapor Technol.

Motivation

— **Thermal barrier coatings (TBCs) can significantly increase gas temperatures, reduce cooling requirements, and improve engine fuel efficiency and reliability**

Combustor Vane Blade Ceramic nozzles

CMC combustor liner and vane



(a) Current TBCs (b) Advanced TBCs

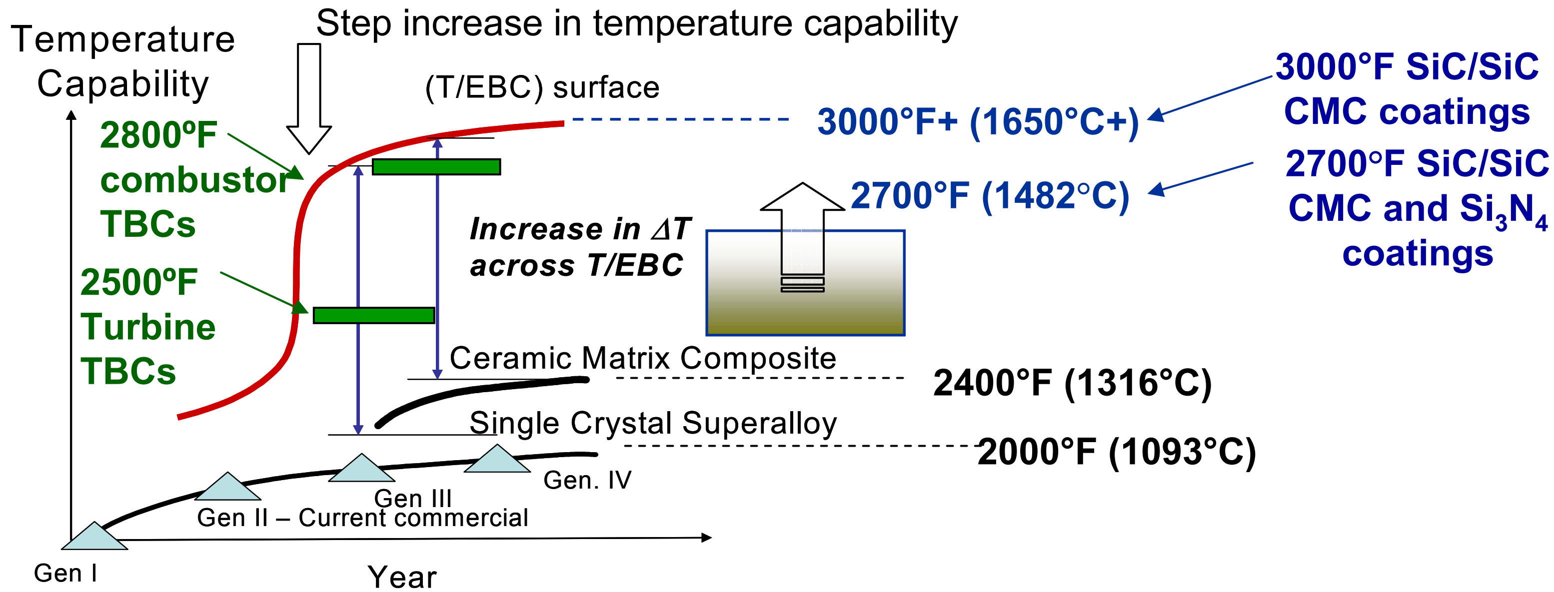
NASA Ceramic Coating Development Goals

— Meet engine temperature and performance requirements
  - improved engine efficiency
  - reduced emission
  - increase long-term durability

— Improve technology readiness

— The programs require a step-increase in coating capability

— Reliability critical



Outline

- **Simulated high-heat-flux testing approaches**
  - Laser high heat flux
  - Burner and laser high temperature erosion
  - High pressure burner and high heat-flux capability
- **Low conductivity thermal barrier coating developments**
  - Low conductivity TBC design requirements
  - Performance of low k four-component TBC systems
    Conductivity, and cyclic durability
  - High toughness Low k four- and six-component turbine airfoil TBC development – erosion resistance
  - CMAS interaction testing
- **Future directions**
- **Summary**

High Heat-Flux Test Approaches

– **High-heat-flux tests crucial for turbine TBC developments**

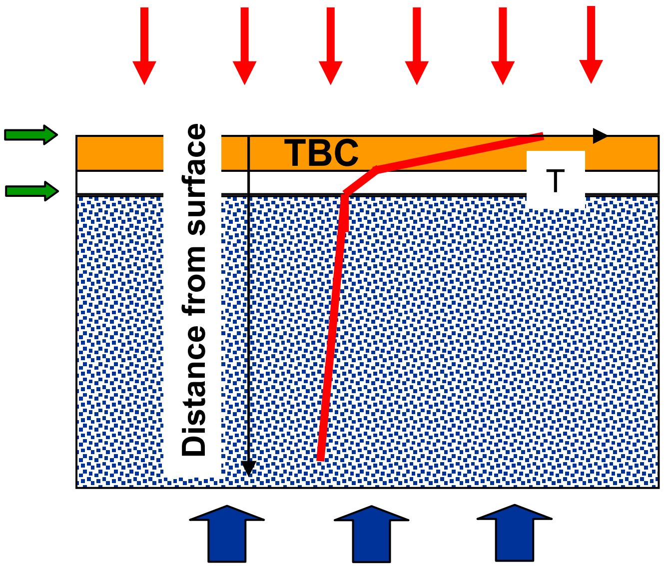
- CO_2 laser simulated turbine engine high-heat-flux rig
- Atmospheric burner rig simulated heat flux testing
- High pressure burner rig simulated engine heat flux and pressure environments

Turbine blade TBC testing requirements

- ΔT ~450°F (250°C) across 5mil coating
- Heat flux up to 400 W/cm²

Heat flux

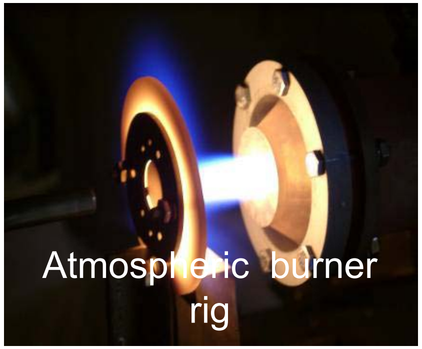
Tsurface
2400-2500°F
(1316-1371°C)
Tinterface
1950°F
(1066°C)

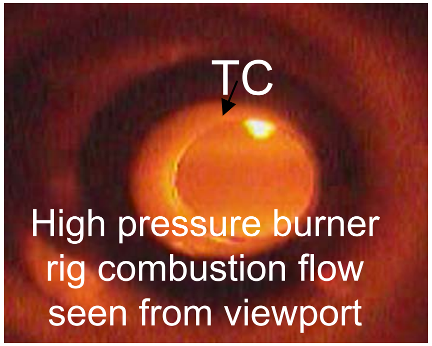


cooling

h_c=0.4 W/cm²-K max

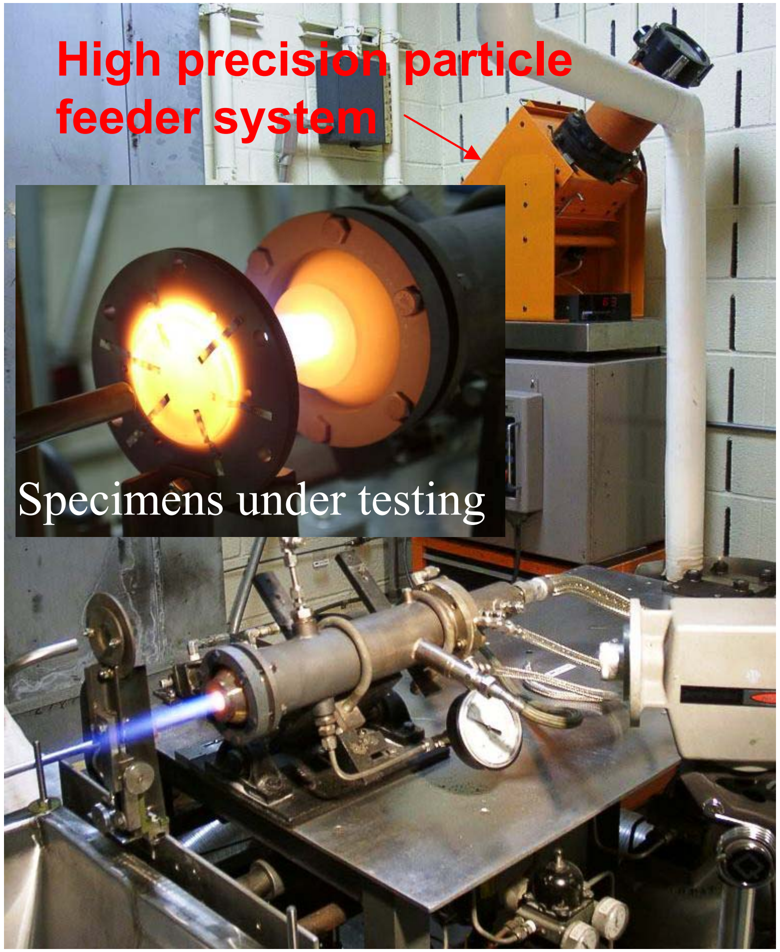

High power CO_2 Laser high heat flux rig


Atmospheric burner rig

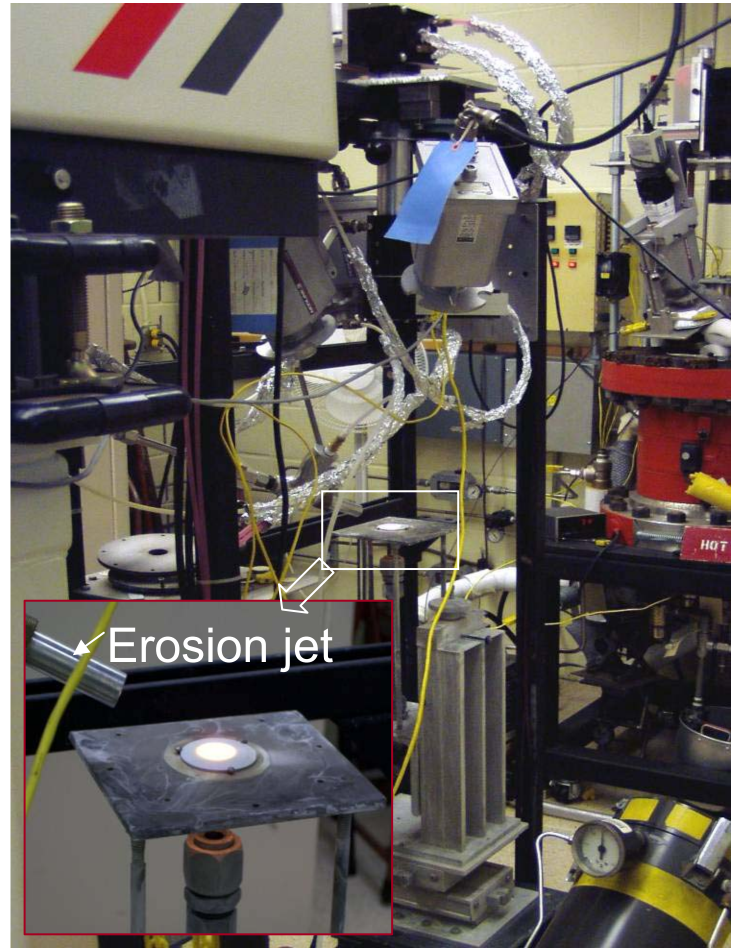


High pressure burner rig combustion flow seen from viewport

High Velocity Burner Erosion Rig and Laser high Heat Flux Erosion Test Rig for Turbine TBC Testing



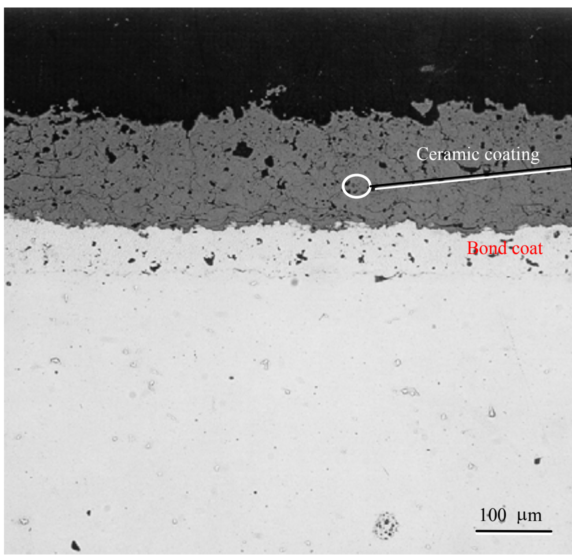
Mach 0.3-1.0 burner erosion rig

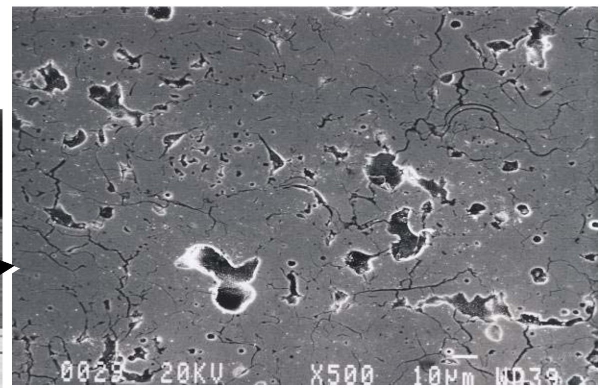


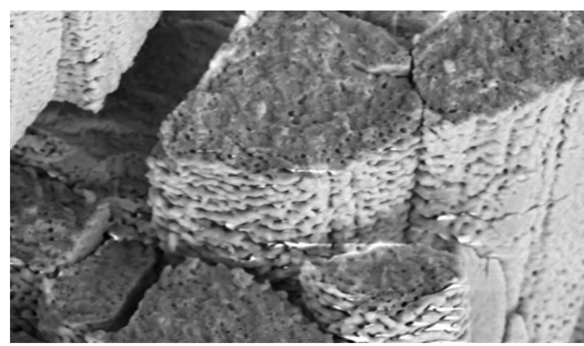
Laser heat flux erosion rig

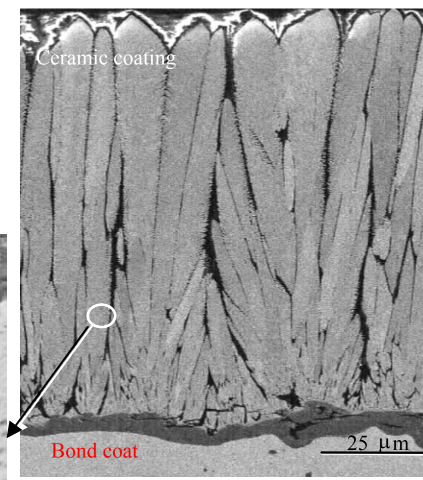
ZrO_2-(7-8) wt%Y_2O_3 Thermal Barrier Coating Systems

- Relatively low intrinsic thermal conductivity ~2.5 W/m-K
- High thermal expansion to better match superalloy substrates
- Good high temperature stability and mechanical properties
- Additional conductivity reduction by micro-porosity







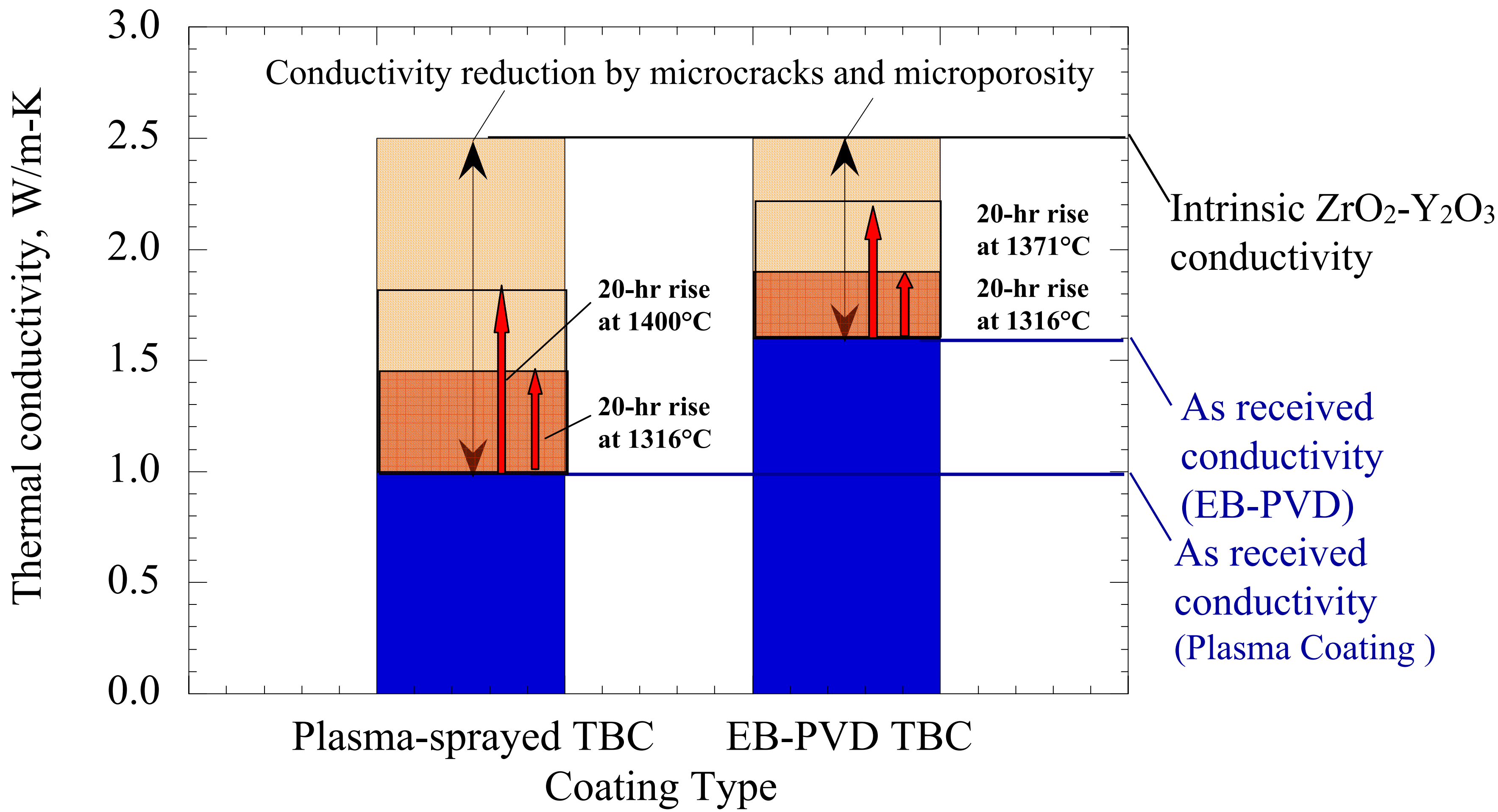


(a) Plasma-sprayed coating

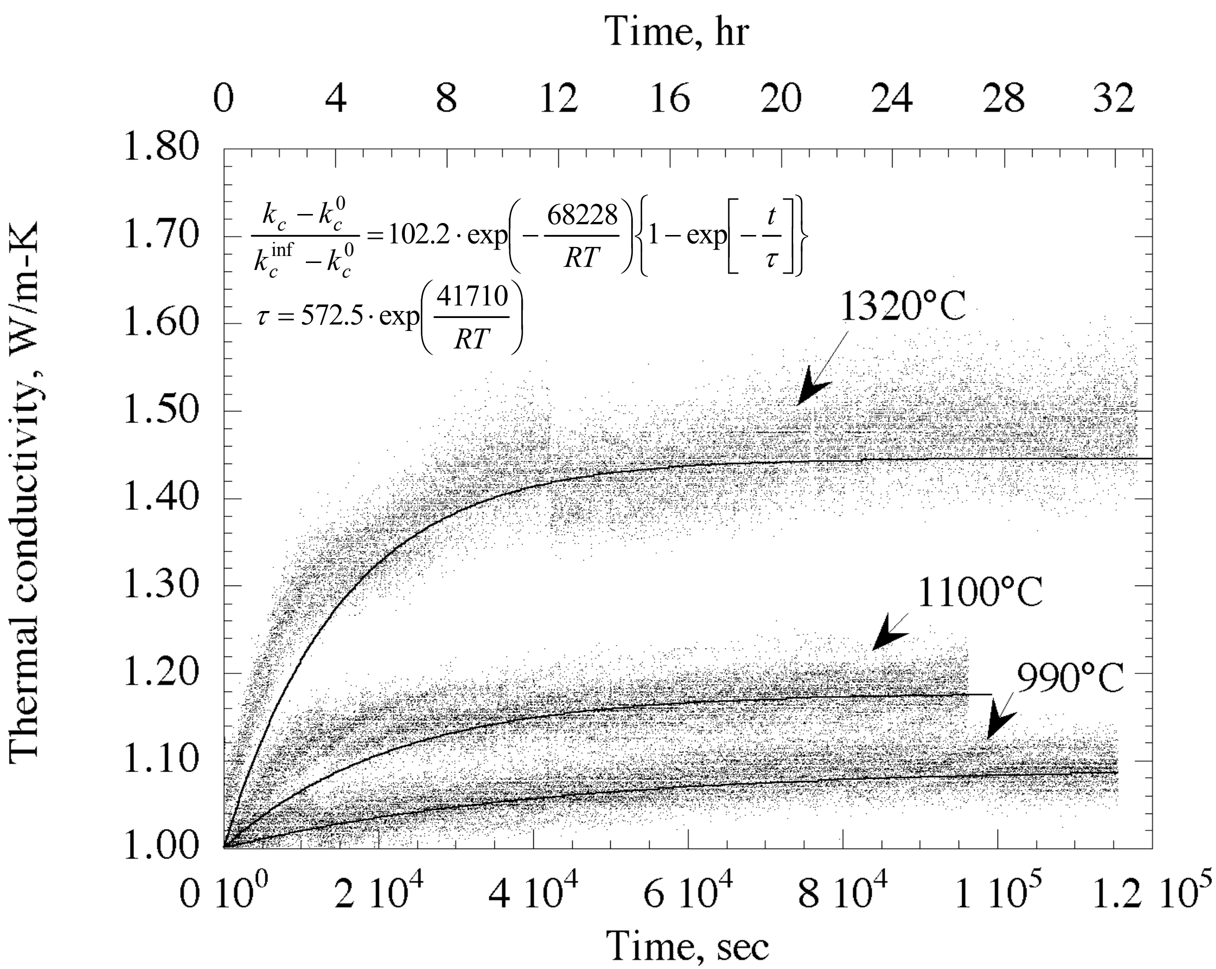
(b) EB-PVD coating

Sintering and Conductivity Increase of ZrO_2-(7-8) wt%Y_2O_3

- Significant conductivity increase at high temperature due to sintering
- Accelerated failure due to phase stability and reduced strain tolerance



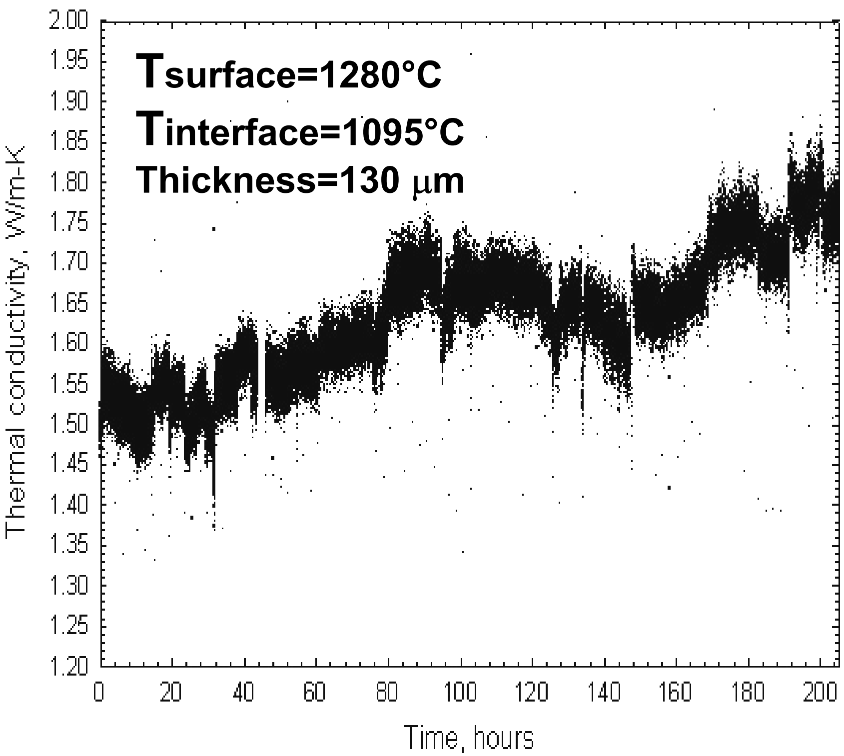
Sintering Kinetics of Plasma-Sprayed ZrO_2-8wt%Y_2O_3 Coatings

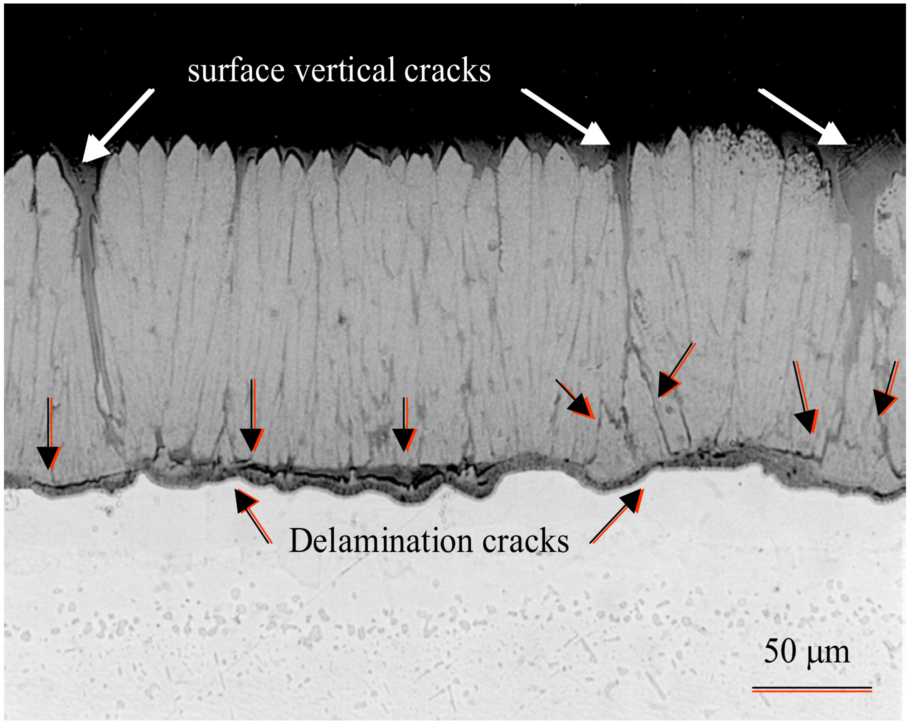


Zhu & Miller, Surf. Coat. Technol., 1998; MRS Bulletin, 2000

Sintering Cracks and Delaminations

— **High heat flux surface sintering cracking and resulting coating delaminations**

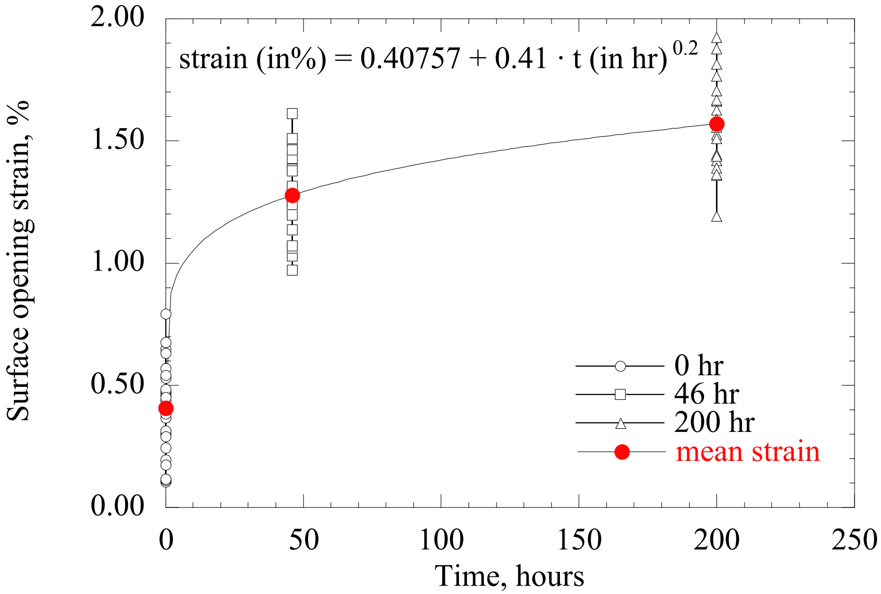


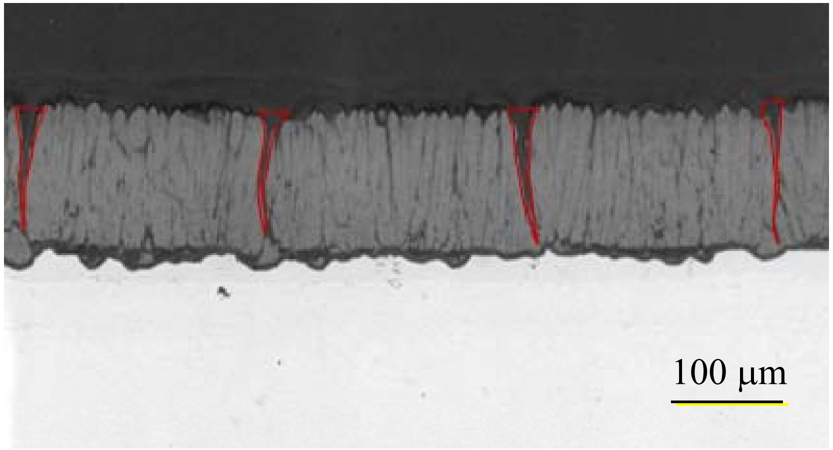


Zhu et al, Surf. Coat. Tech., 138 (2001), 1-8

Sintering Cracks and Delaminations
- continued

— **Sintering strain corresponding to the thermal gradient across the coating ($T_{surface}$=1280°C, $T_{interface}$=1095°F)**





Low Conductivity and Sintering Resistant Thermal Barrier Coating Design Requirements

— Low conductivity (“1/2” of the baseline) retained at 2400°F

— Improved sintering resistance and phase stability (up to 3000°F)

— Excellent durability and mechanical properties

- Cyclic life
- Toughness
- Erosion/impact resistance
- CMAS and corrosion resistance
- Compatibility with the substrate/TGO

— Processing capability using existing infrastructure and alternative coating systems

— Other design considerations

- Favorable optical properties
- Potentially suitable for various metal and ceramic components
- Affordable and safe

Low Conductivity Thermal Barrier Coating Design Approaches

– **Efforts on modifying coating microstructures and porosity, composite TBCs, or alternative oxide compounds**

– **Emphasize ZrO_2- or HfO_2-based *alloy* systems – defect cluster approach for toughness consideration**

– **Advantages of defect cluster approach**

- **Advanced design approach:** design of the clustering
- **Better thermal stability:** point defects are thermodynamically stable
- **Improved sintering resistance:** effective defect concentration reduced and activation energies increased by clustering
- **Easy to fabricate:** plasma-sprayed or EB-PVD processes

Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings

— **Multi-component oxide defect clustering approach (Zhu and Miller, US Patents No. 6,812,176, No.7,001,859, and No. 7,186,466)**

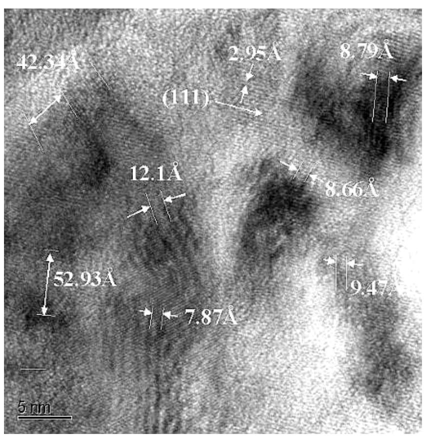
e.g.: ZrO_2-Y_2O_3-Nd_2O_3(Gd_2O_3,Sm_2O_3)-Yb_2O_3(Sc_2O_3) systems

Primary stabilizer

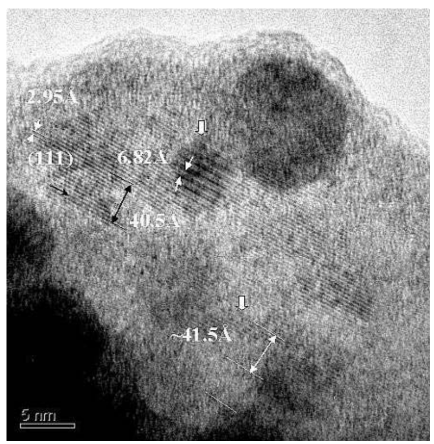
Oxide cluster dopants with distinctive ionic sizes

— **Defect clusters associated with dopant segregation**

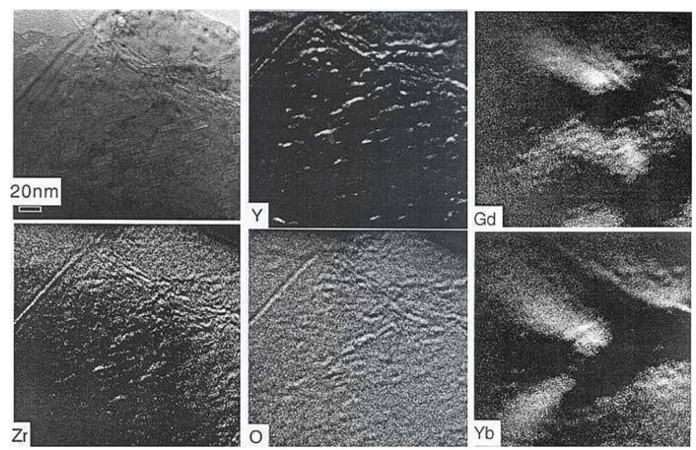
— **The nanometer sized clusters for reduced thermal conductivity, improved stability, and mechanical properties**



Plasma-sprayed ZrO_2-(Y, Nd,Yb)$_2O_3$



EB-PVD ZrO_2-(Y, Nd,Yb)$_2O_3$

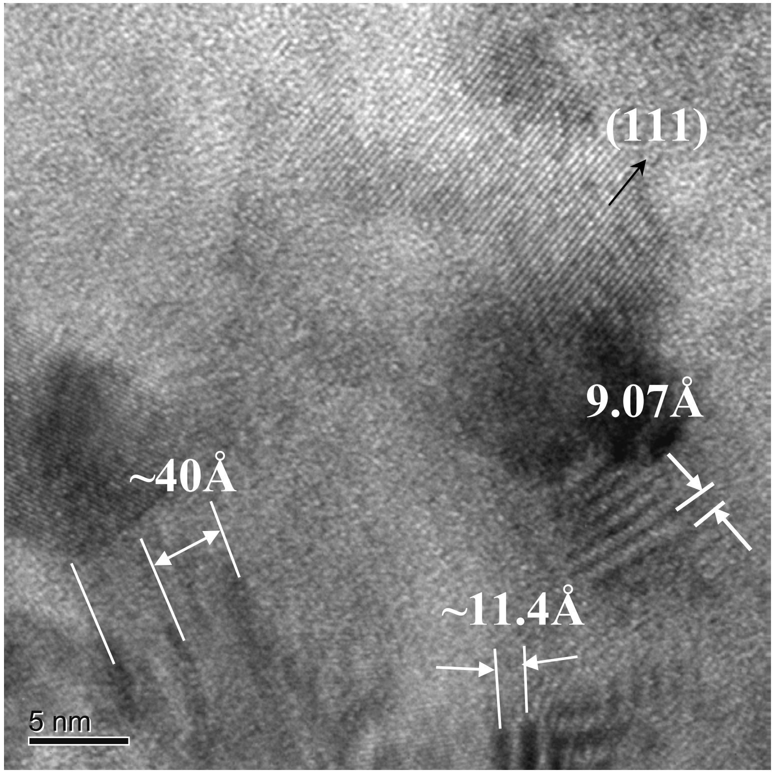


EELS elemental maps of EB-PVD ZrO_2-(Y, Gd,Yb)$_2O_3$

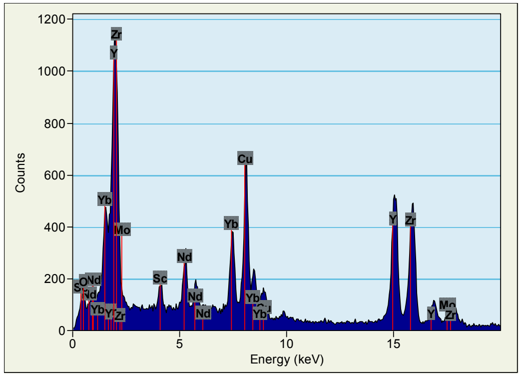
Zhu et al, Ceram. Eng. Sci. Proc., 2003

Defect Clusters in a Plasma-Sprayed Y_2O_3, Nd_2O_3 and Yb_2O_3 Co-Doped ZrO_2-Thermal Barrier Coating

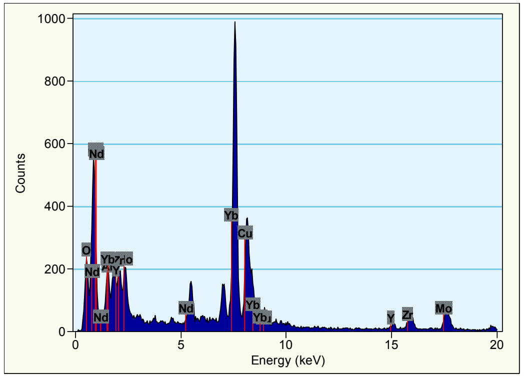
— Yb, Nd rich regions consisting of small clusters with size of 5 to 20 nm



Yb, Nd rich region clusters



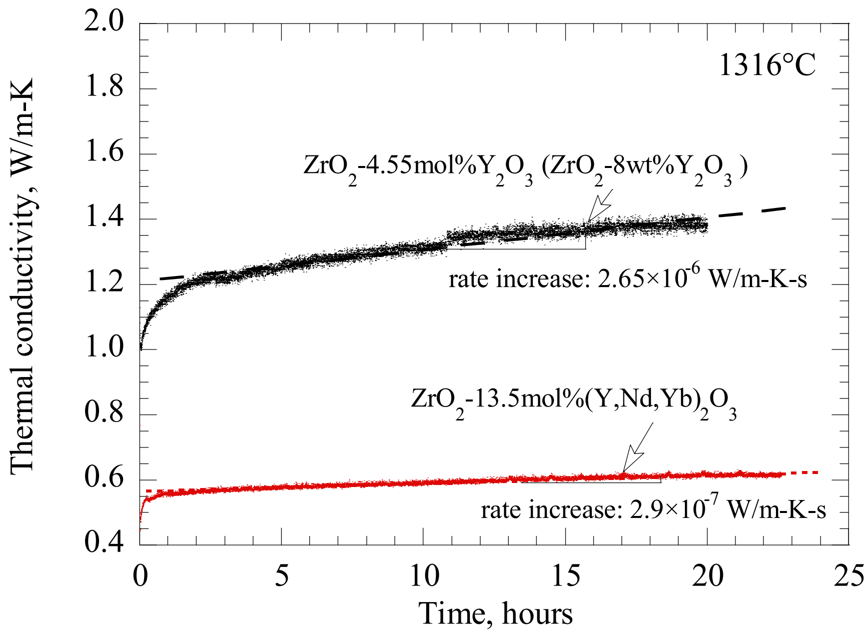
Overall EDS



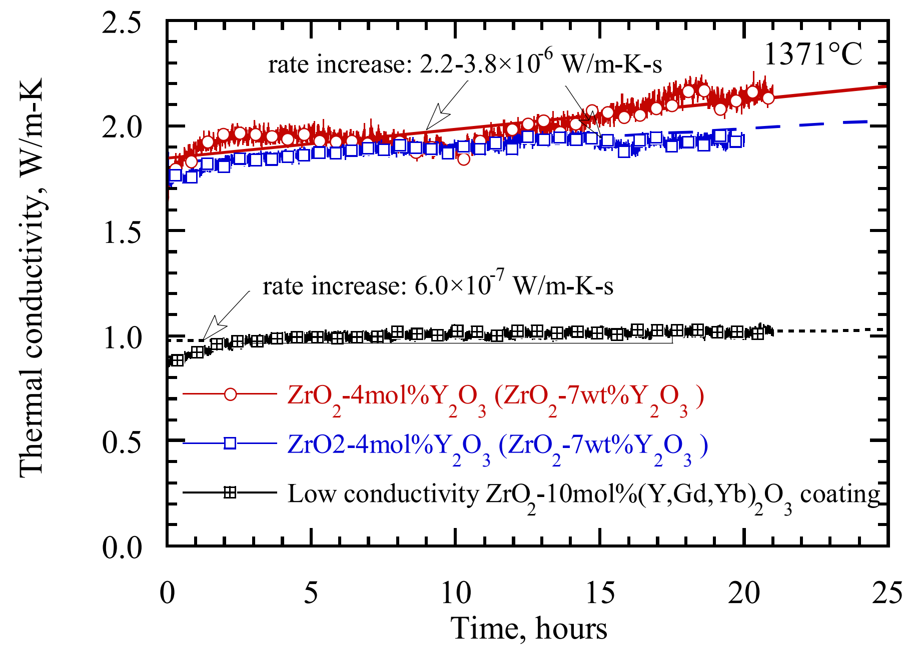
Yb rich region EDS

Low Conductivity Defect Cluster Coatings Demonstrated Improved Thermal Stability

— **Thermal conductivity significantly reduced at high temperatures for the low conductivity TBCs**

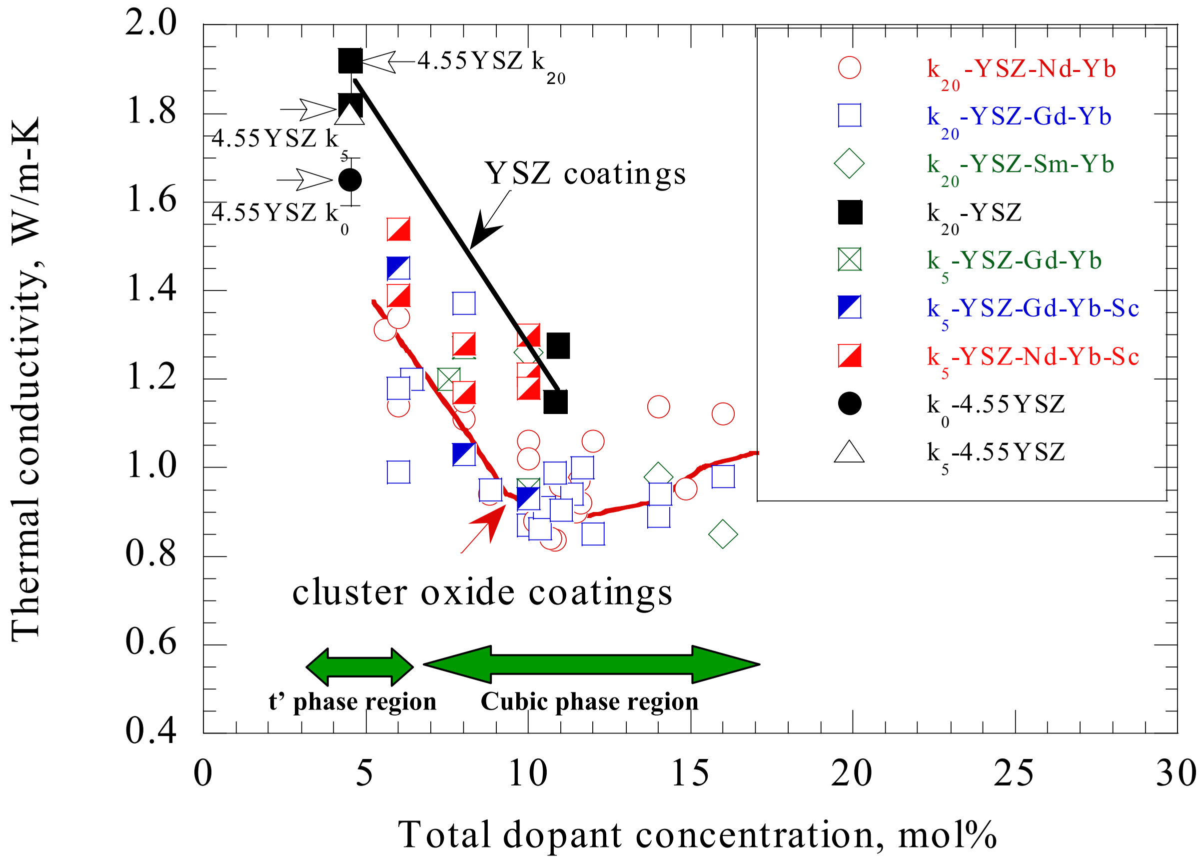


(a) Plasma-sprayed coatings



(b) EB-PVD coatings

Thermal Conductivity of Defect Cluster Thermal Barrier Coatings

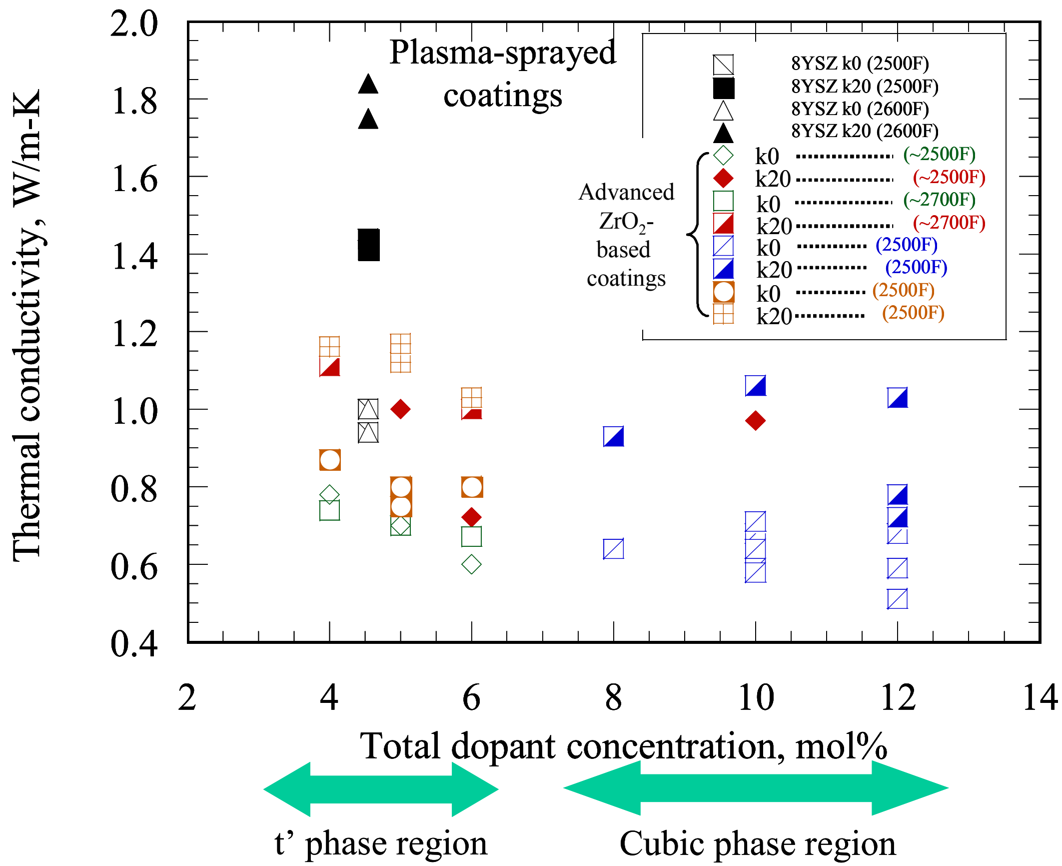


EB-PVD coatings

(k_0, k_5 and k_{20} are the initial thermal conductivity, and the conductivity at 5 and20 hours, respectively)

Thermal Conductivity of Defect Cluster Thermal Barrier Coatings

— **Thermal conductivity benefit of oxide defect cluster thermal barrier coatings demonstrated**



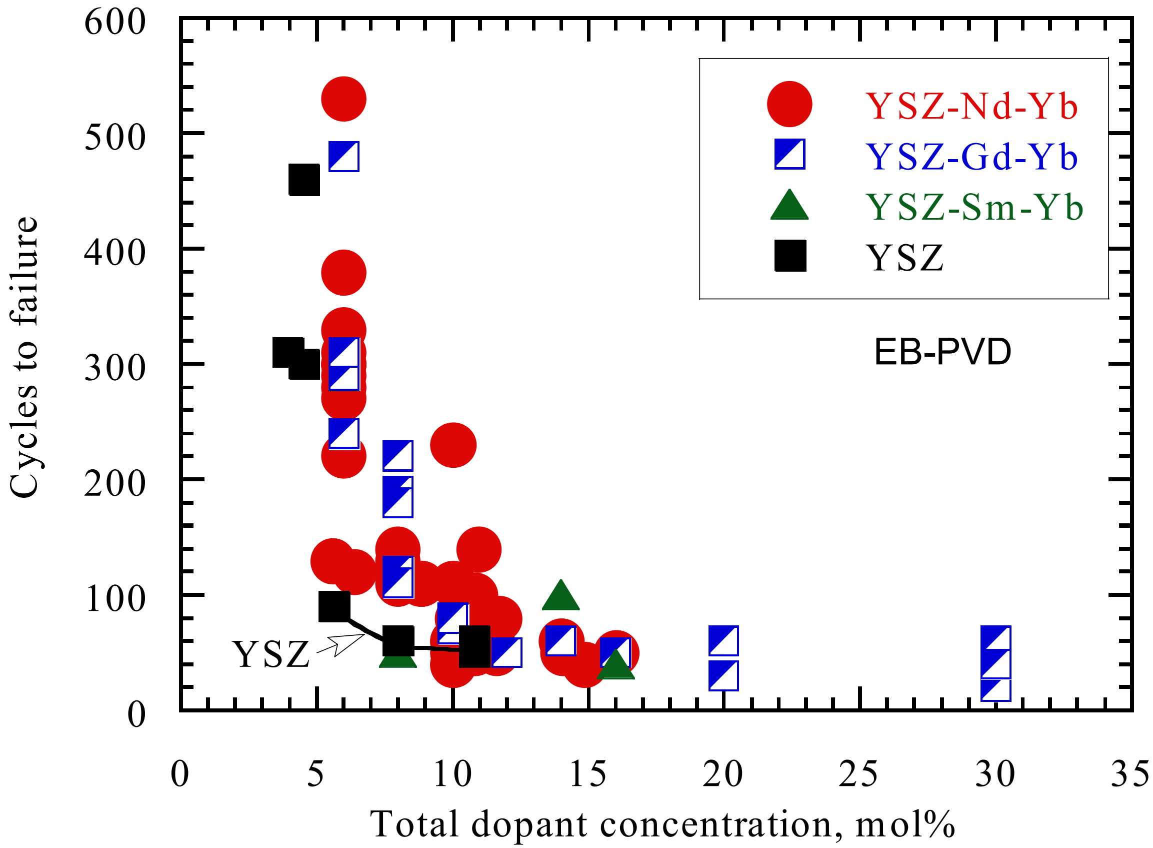
Plasma-sprayed coatings

(k_0, and k_{20} are the initial thermal conductivity, and the conductivity at 5 and20 hours, respectively)

Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ Thermal Barrier Coatings

— t' low k TBCs had good cyclic durability

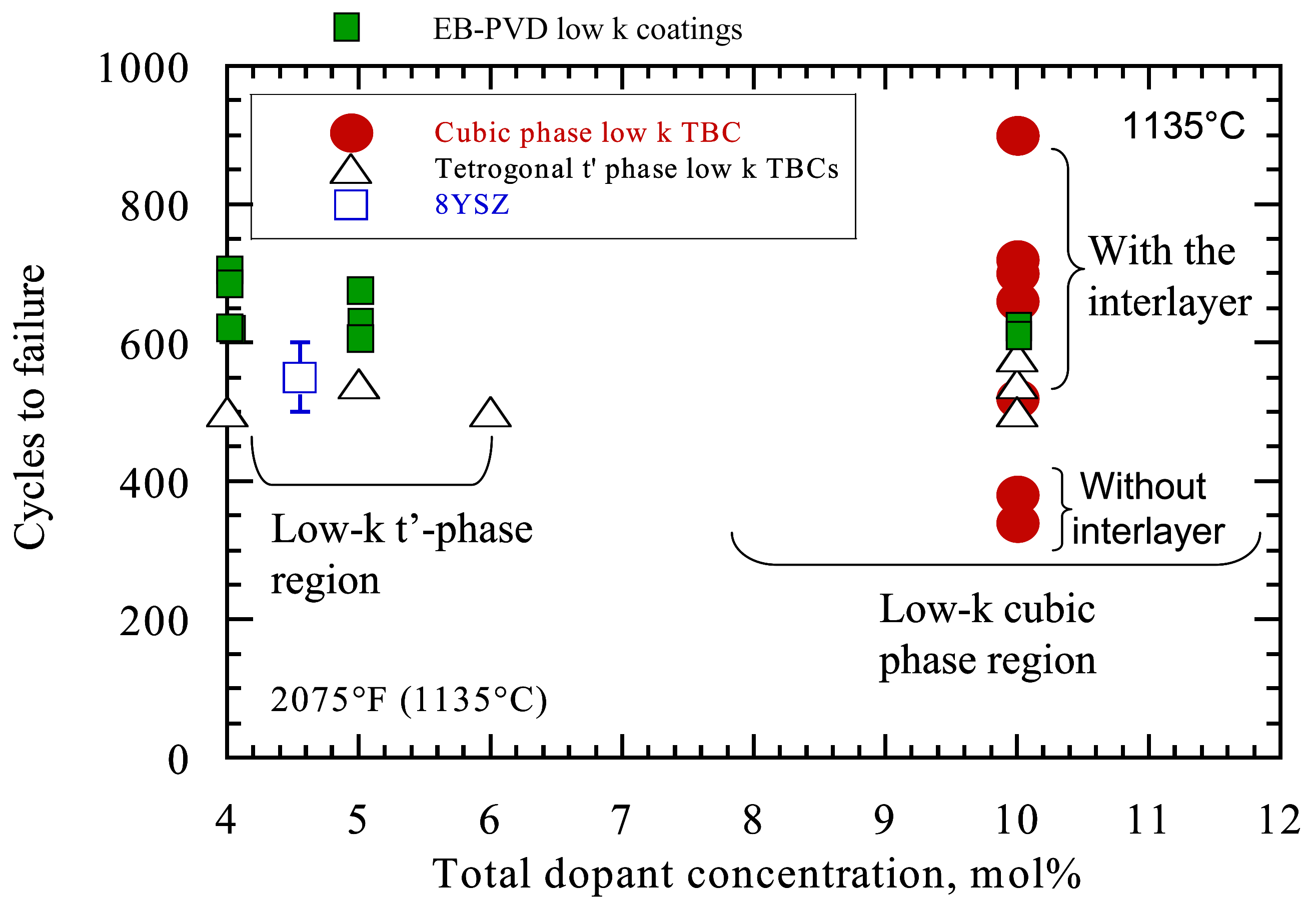
— The cubic-phase low conductivity TBC durability needed improvements



Zhu and Miller, Ceram. Sci. Eng. Proc., 2002

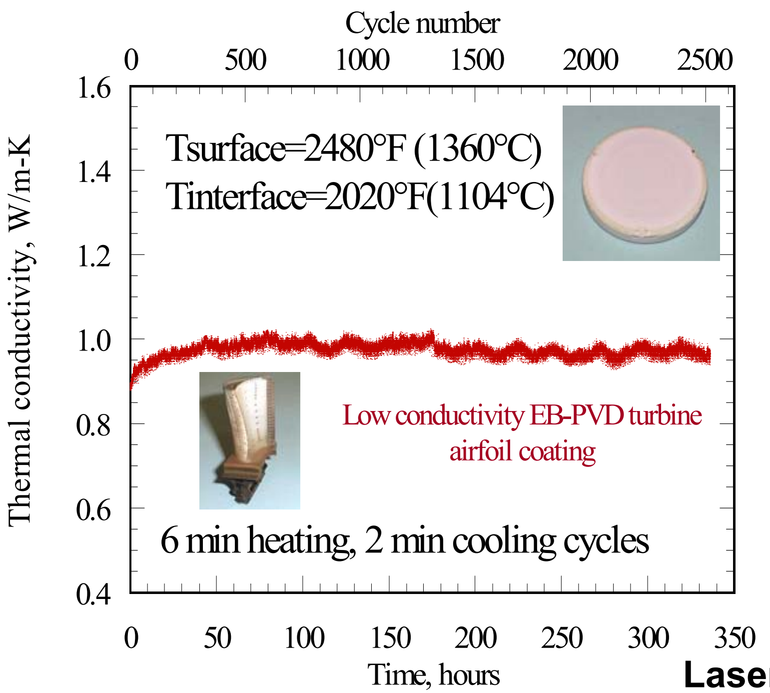
Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ Thermal Barrier Coatings - Continued

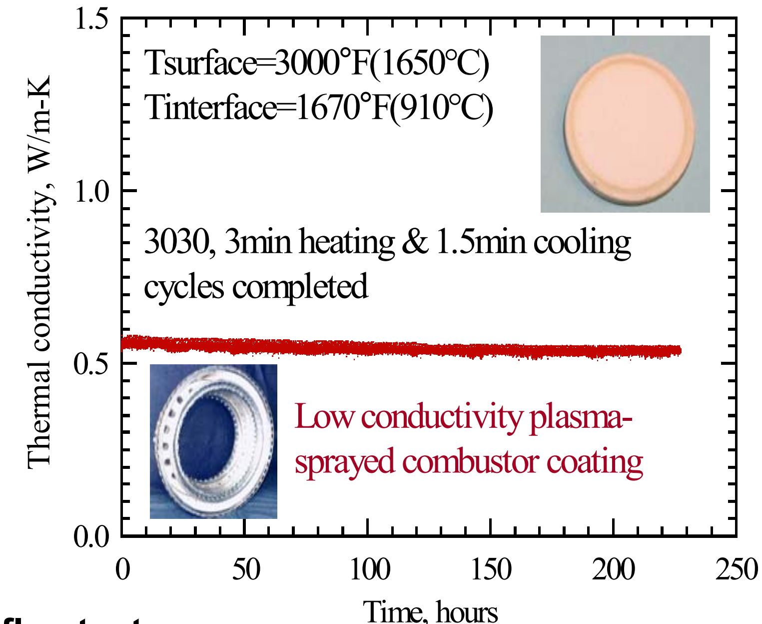
- t' low k TBCs had good cyclic durability
- The cubic-phase low conductivity TBC durability initially improved by an 7YSZ or low k t'-phase interlayer



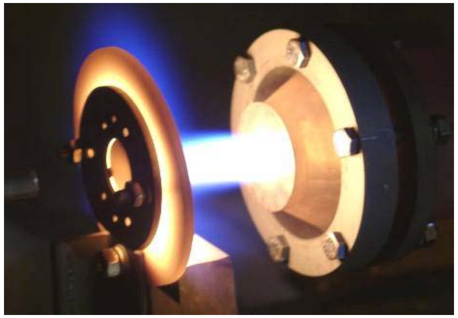
Advanced Low Conductivity TBC Showed Excellent Cyclic Durability

— Coating validated for down-selected low conductivity coating systems





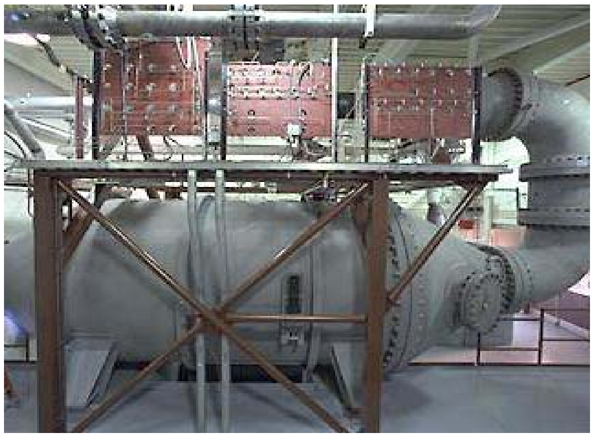
Laser heat flux tests



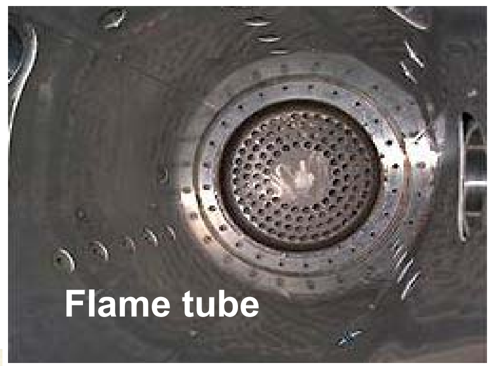
Burner rig tests

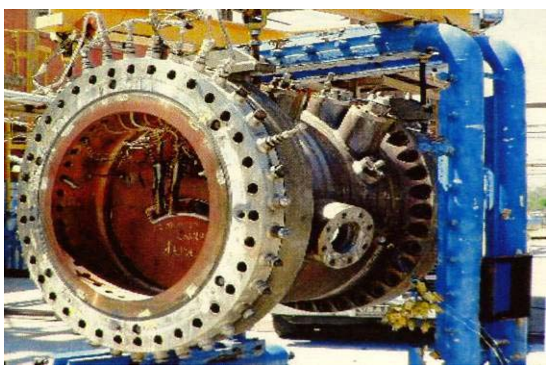
Advanced Low Conductivity Combustor Thermal Barrier Coating Developments

- Low k TBC coated components demonstrated in simulated engine environments
- Low k TBC being incorporated in advanced engine development programs

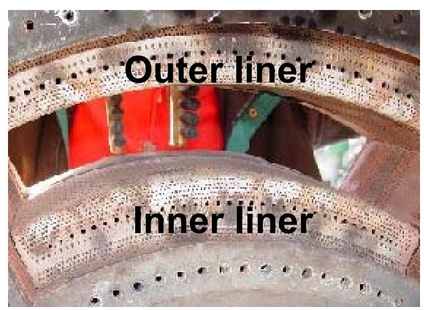


Low conductivity TBC flame tube and combustor deflector demos in Advanced Subsonic Combustion Rig (ASCR)





Low conductivity TBC combustor liner demonstration in Combustor rig

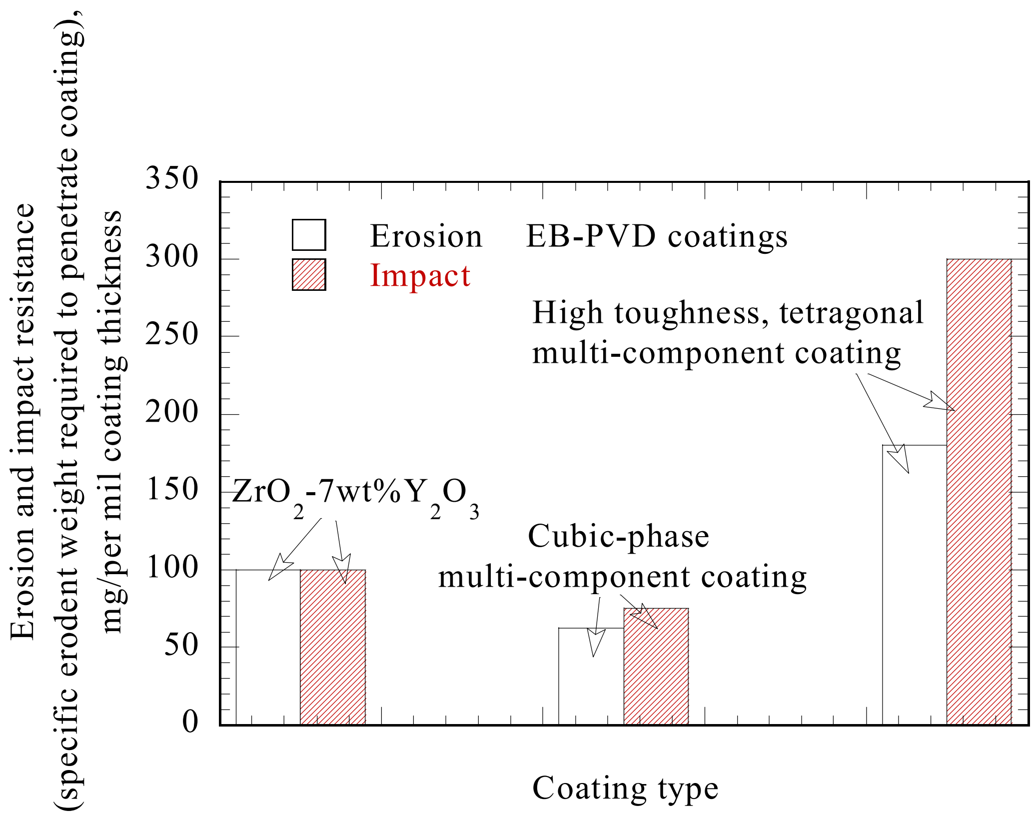


Low conductivity TBC: combustor liner demonstration

Low conductivity TBC Propulsion 21 flame tube and deflector demonstrations

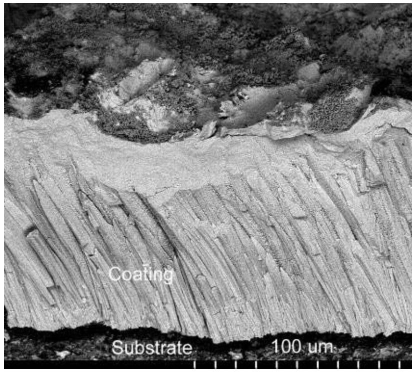
Erosion and Impact Resistant Turbine TBC Development

— **Multi-component ZrO_2 low k coatings showed promise in improving erosion and impact resistance**



Zhu & Miller, NASA R&T, 2004

Erosion and impact resistance, measured as the erodent Al_2O_3 weight required to penetrate unit thickness coating



2200°F burner rig erosion

Advanced Multi-Component Erosion Resistant Turbine Blade Thermal Barrier Coating Development

- **Rare earth (RE) and transition metal oxide defect clustering approach** (*US Patents No. 6,812,176, No.7,001,859, and 7,186,466; US patent application 11/510,574*) specifically by additions of RE_2O_3 , TiO_2 and Ta_2O_5
- **Significantly improved toughness, cyclic durability and erosion resistance while maintaining low thermal conductivity**
- **Improved thermal stability due to reduced diffusion at high temperature**

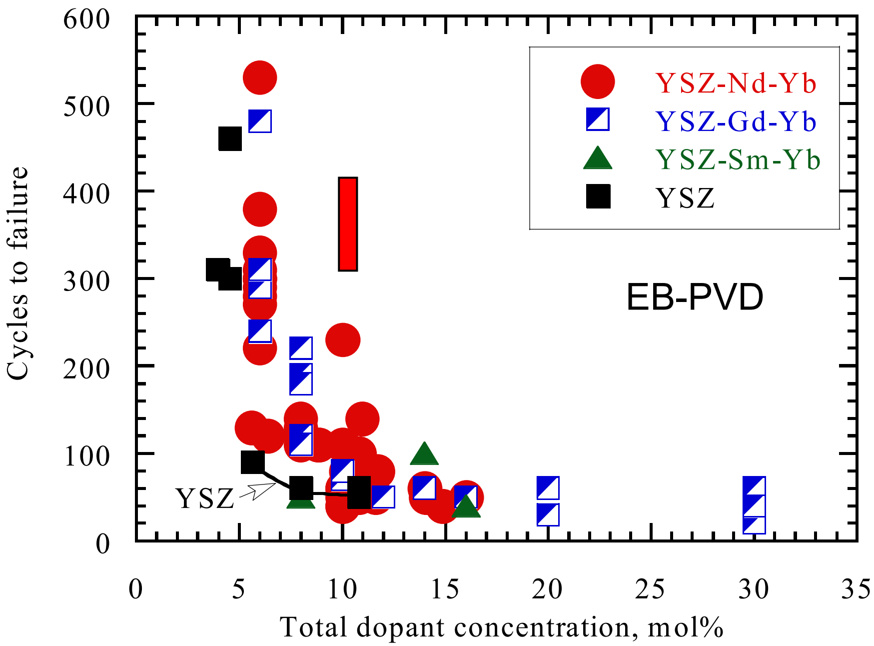
ZrO_2-Y_2O_3- RE1 {e.g.,Gd_2O_3,Sm_2O_3}-RE2 {e.g.,Yb_2O_3,Sc_2O_3} – TT{TiO_2+Ta_2O_5} systems

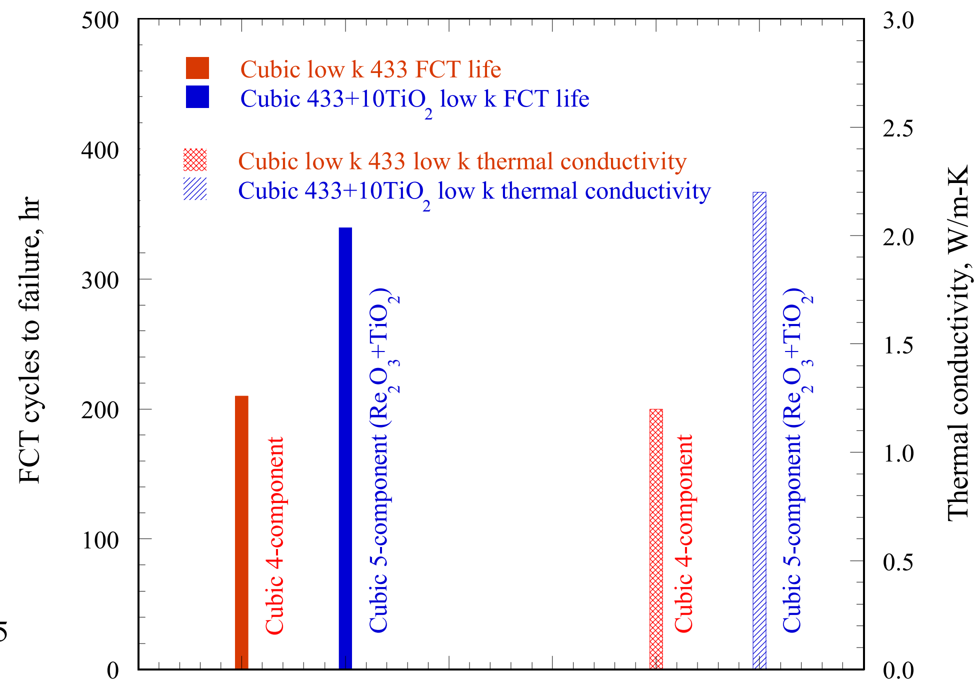
Primary stabilizer

Toughening dopants

Oxide cluster dopants with distinctive ionic sizes

Furnace Cyclic Test Lifetime and Thermal Conductivity of TiO_2 Doped Thermal Barrier Coatings

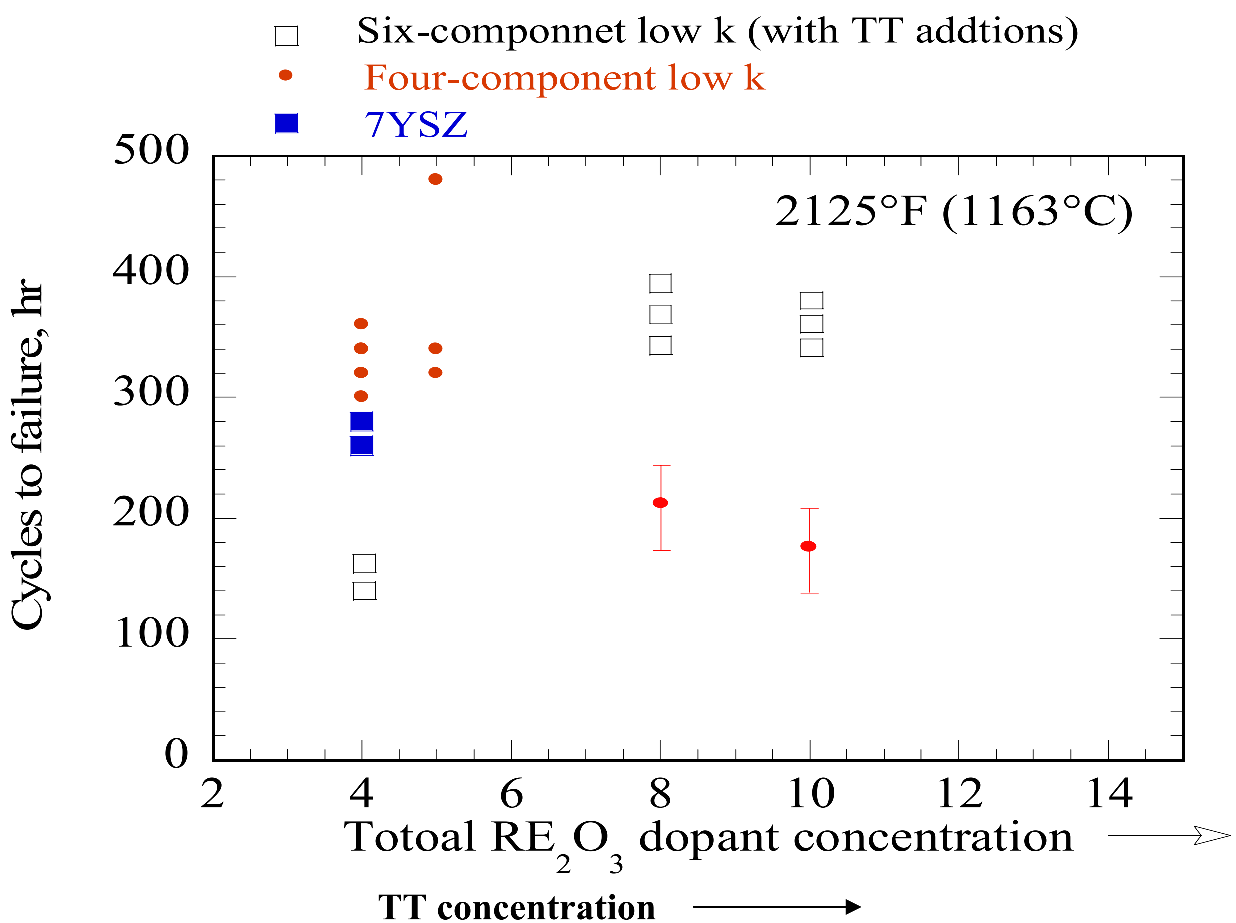




— Unpublished work 2003

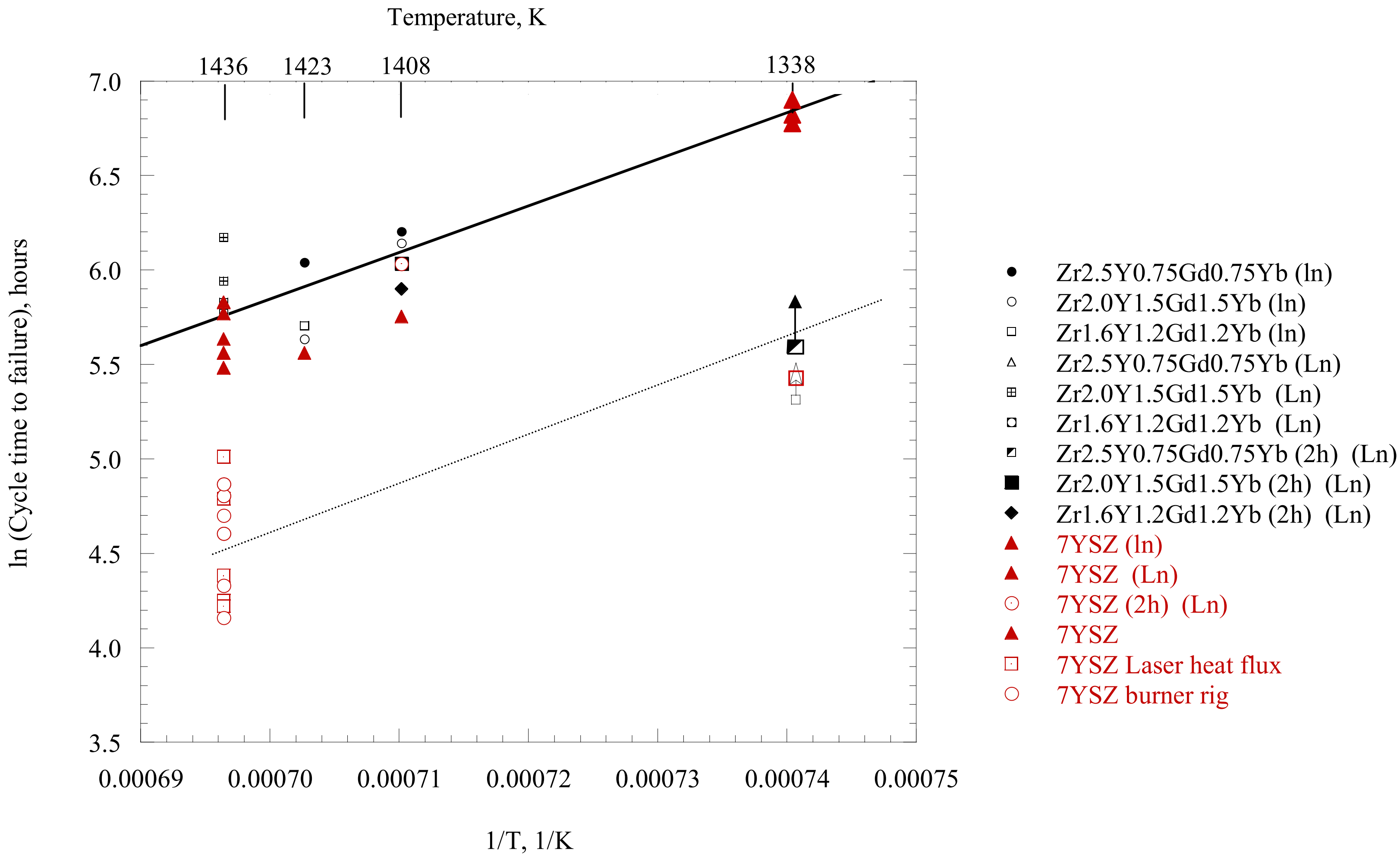
Furnace Cyclic Lifetime of Advanced Turbine Thermal Barrier Coatings

– **Furnace cyclic life can be optimized with RE_2O_3 and TT additions**
– **Stability and volatility with too high TT concentrations**

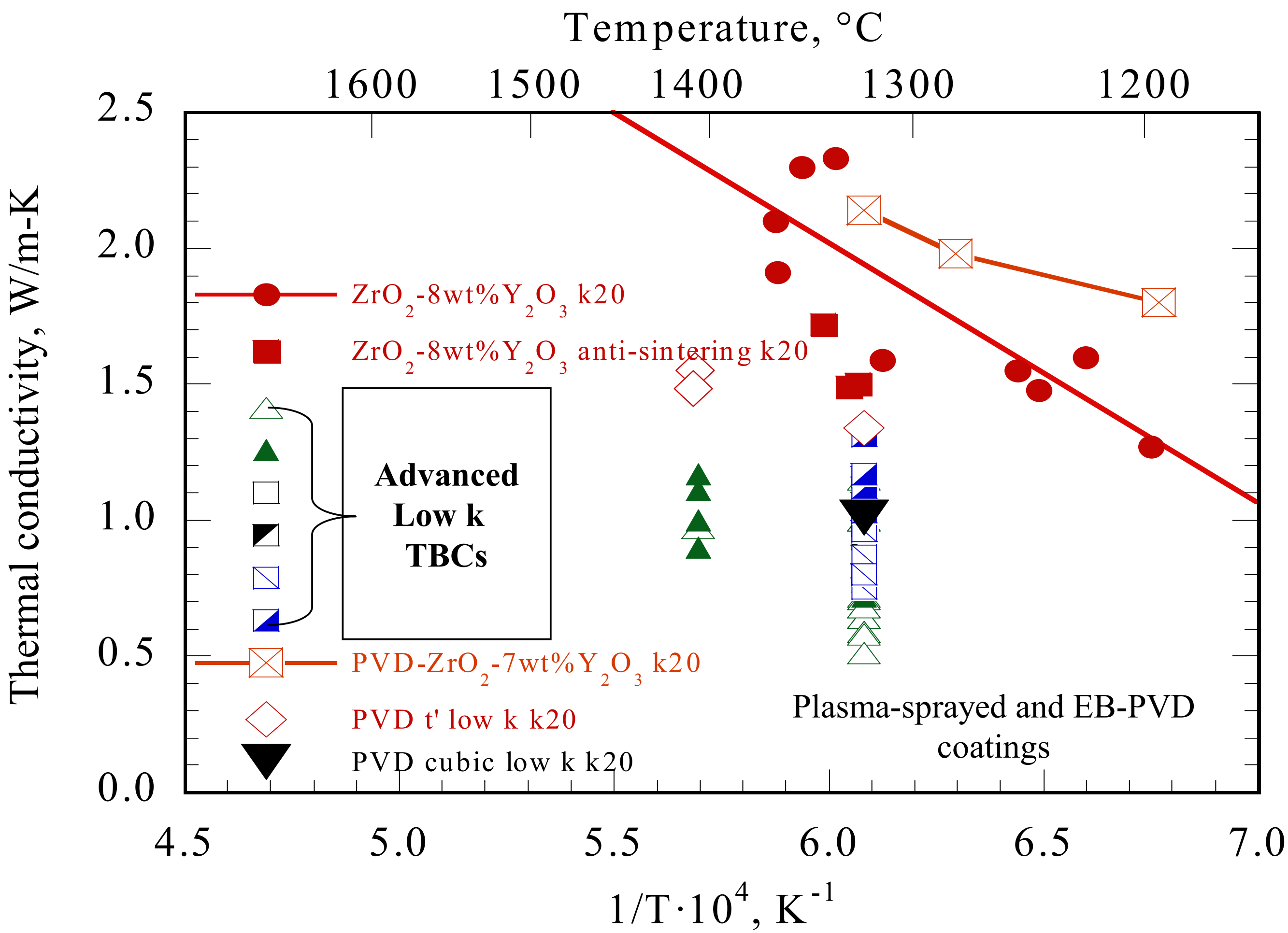


Cyclic Life of Four-Component Thermal Barrier Coatings

– **Furnace and high heat flux cyclic life being optimized for long-term durability**

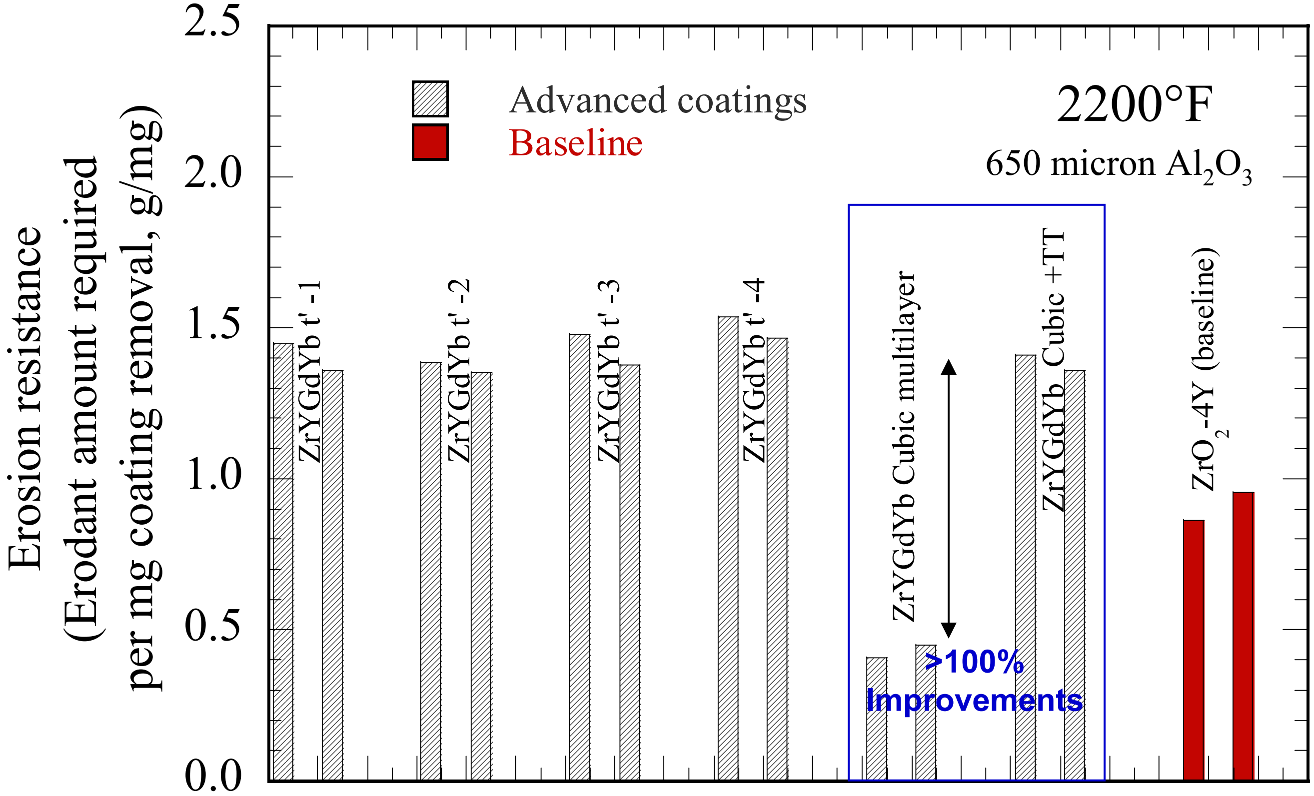


Thermal Conductivity of Selected Low k Thermal Barrier Coatings



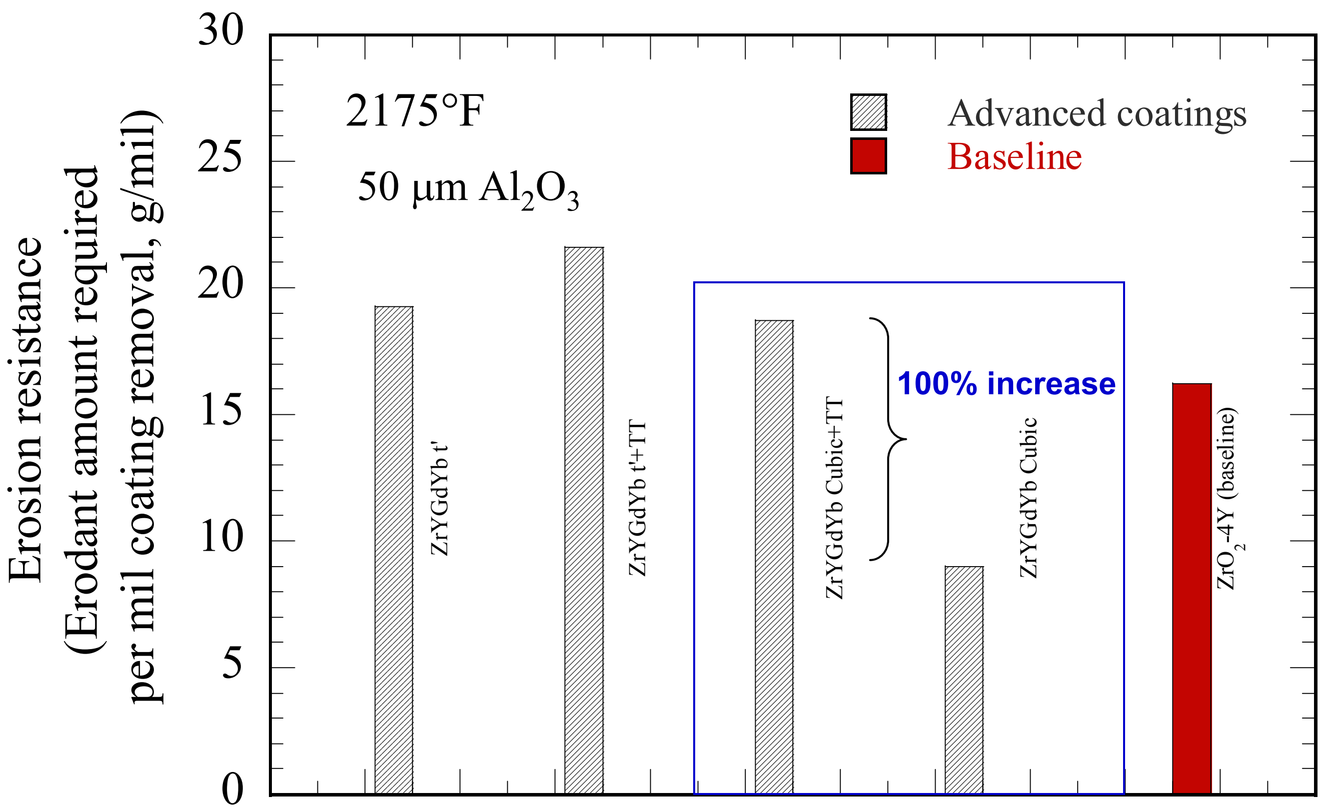
Impact Resistance of Advanced Multi-component Low Conductivity Thermal Barrier Coatings

— **Improved impact/erosion resistance observed for advanced low conductivity six-component coatings**



Erosion Resistance of Advanced Multi-component Low Conductivity Thermal Barrier Coatings

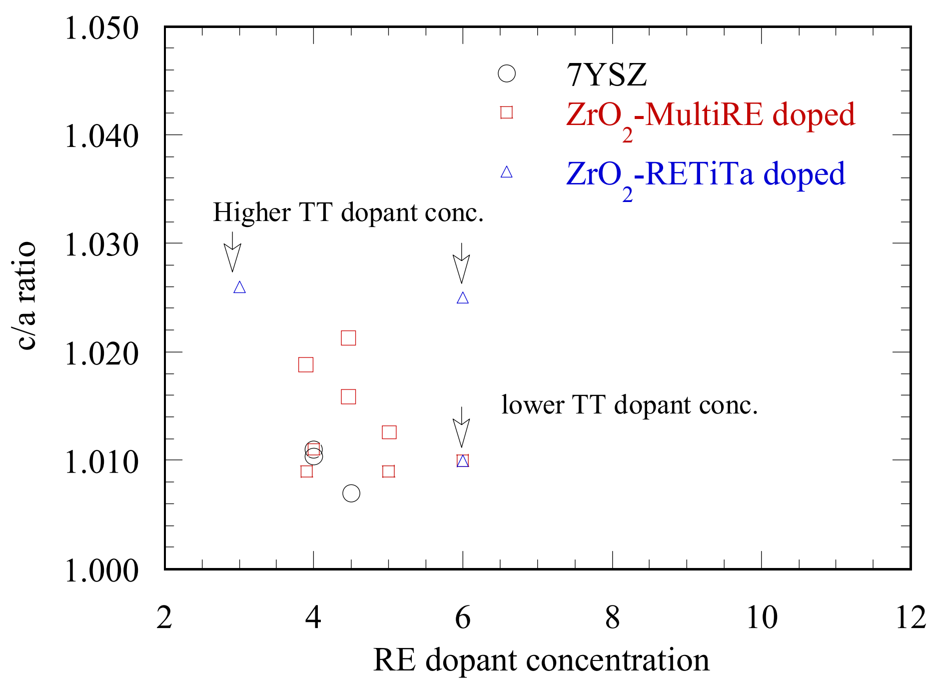
– **The original cubic low k coating showed significant increase in erosion resistance due to the incorporation of TiO_2 and Ta_2O_5**

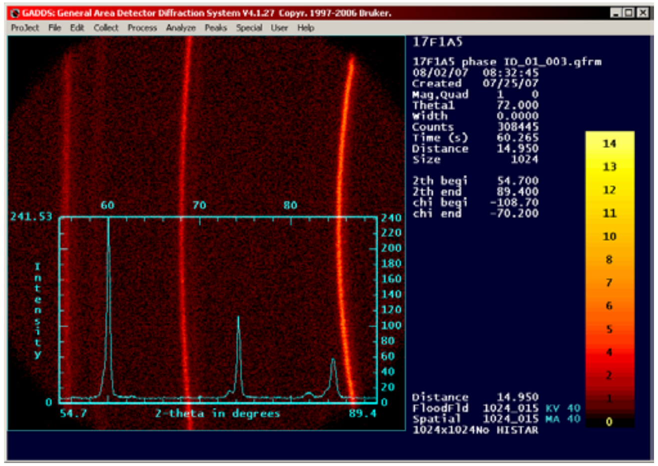


Tetragonality of Multi-Component ZrO_2 being Evaluated and Correlated to Coating Performance

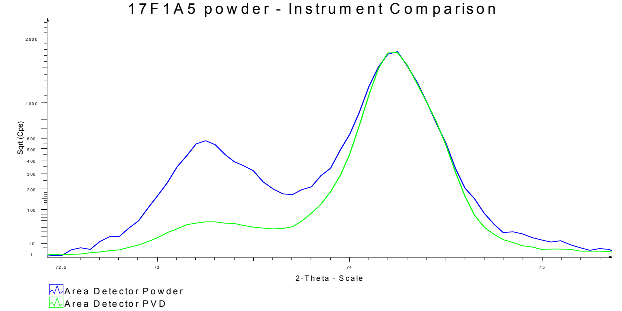
— Multi-component TiO_2/Ta_2O_5 and rare earth dopants increase the tetragonality (c/a ratio)

— Current efforts in optimizing the dopant composition ranges





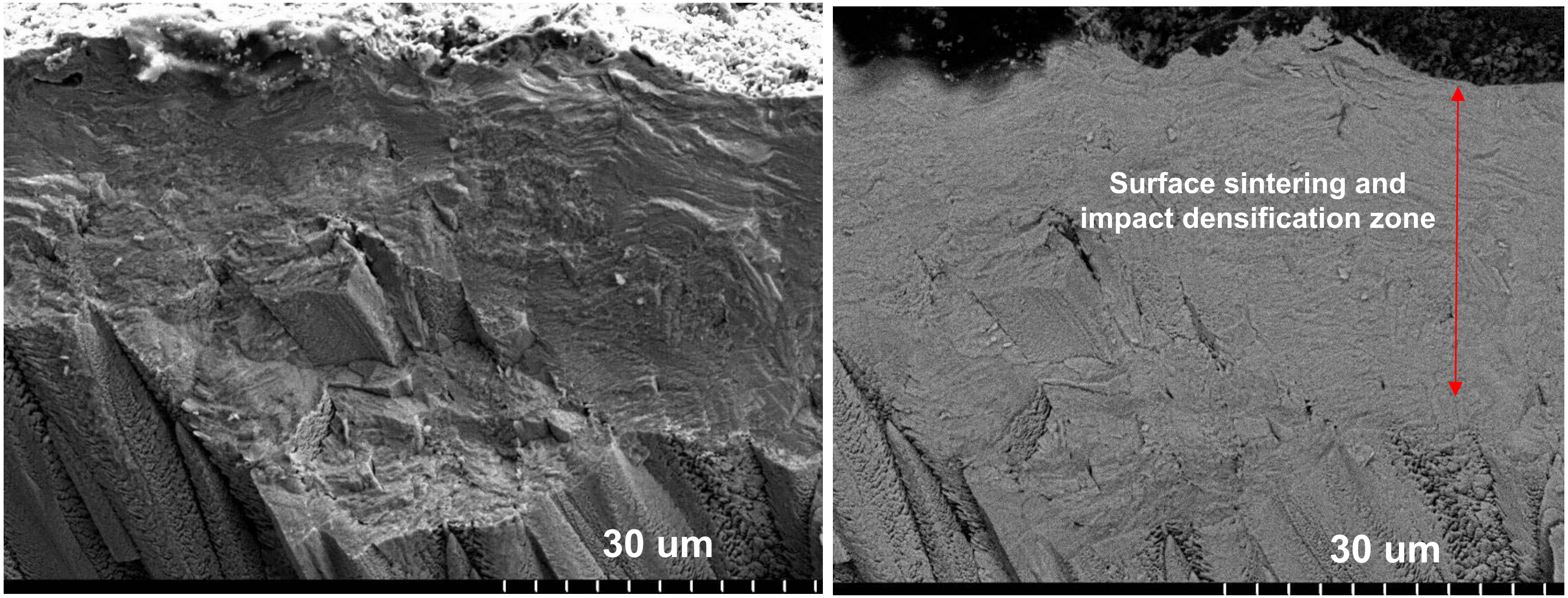
Area detector x-ray diffractometer used for EB-PVD coatings



Impact Failure of Advanced Multi-Component Low Conductivity Thermal Barrier Coatings

— Surface sintering and impact densification zones observed, with subsequent spallation under the erodent further impacts
— Toughened structures observed

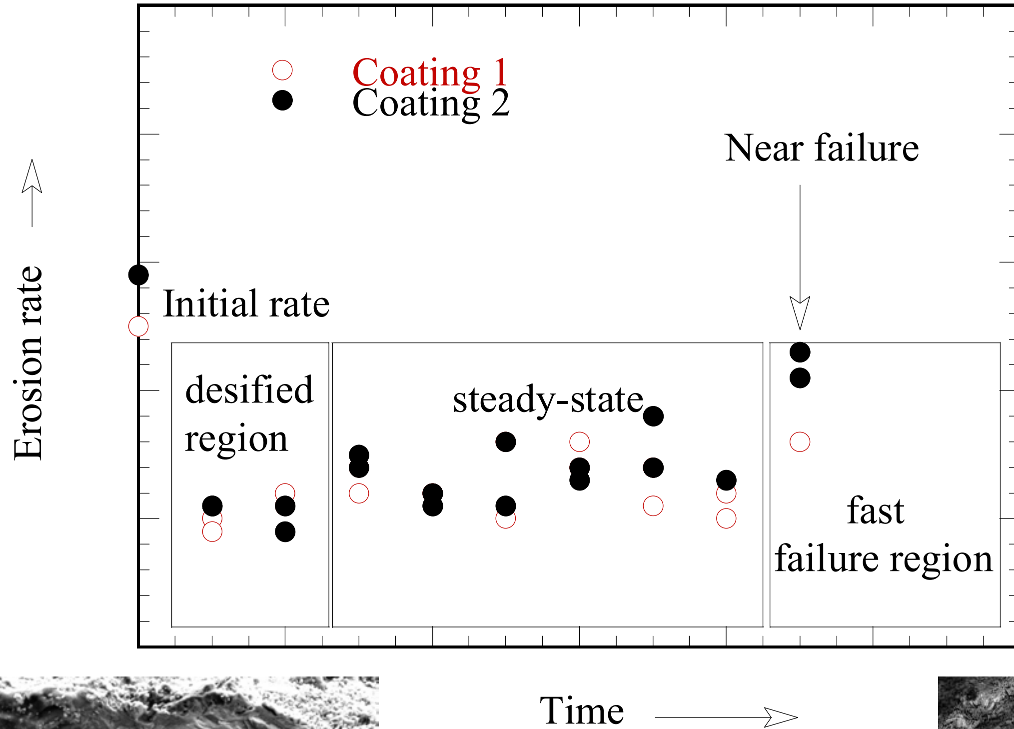
SEM micrographs of advanced thermal barrier coating after impact/erosion damage

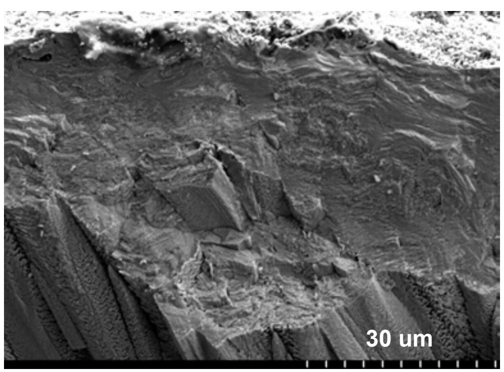


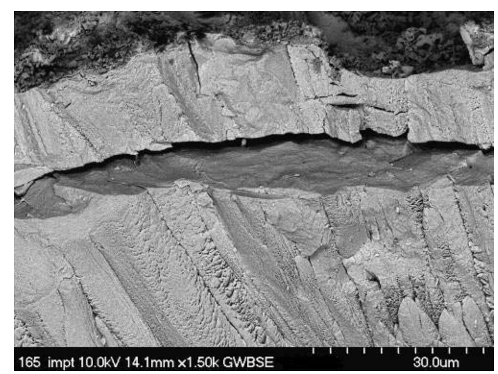
Secondary electron image **Backscattered electron image**

Impact Failure of Advanced Multi-Component Low Conductivity Thermal Barrier Coatings

– Effect of erosion parameters will be modeled and validated

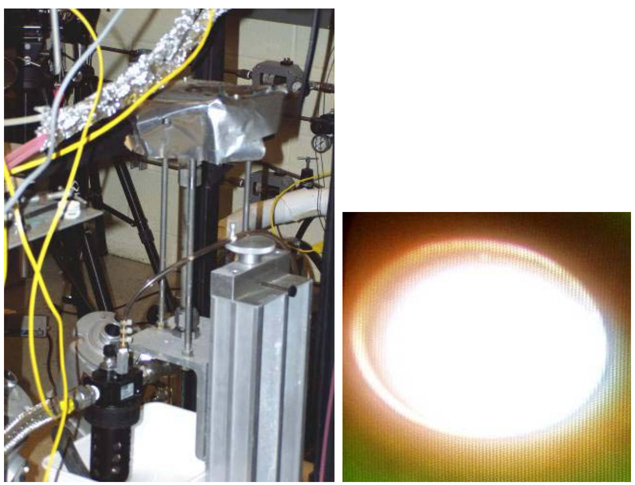




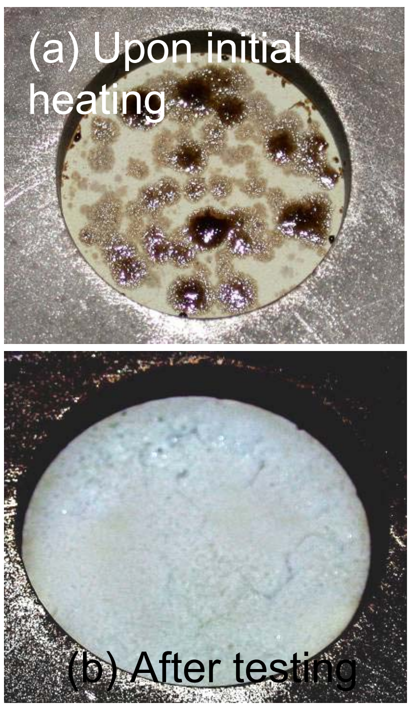


High Heat Flux Testing of Turbine EB-PVD Thermal Barrier Coatings to Study CMAS Effect

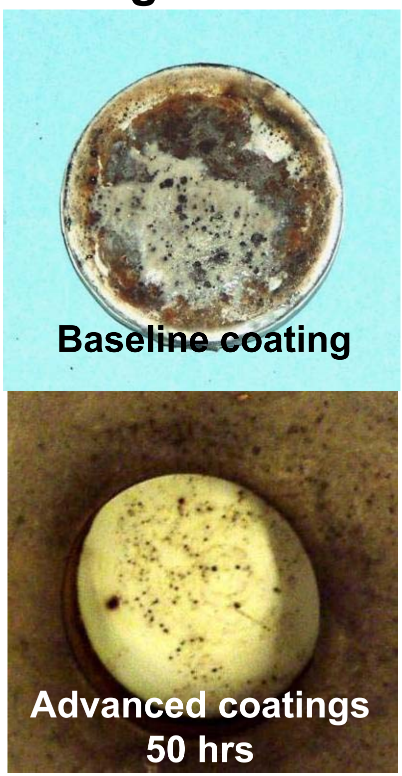
- Specimens typically tested at Tsurface ~2400ºF, Tinterface 2000°F
- Heat flux up to 250-300 W/cm^2, cooling heat transfer coefficient up to h_c 0.32 W/cm^{2}-K
- Accelerated failure observed with CMAS interactions
- Advanced multi-component coatings completed 50 hr testing



Specimen under the rig test



Combustor TBC



Turbine TBCs

Future Directions for Low Conductivity TBC Development

— **Emphasize high heat flux durability and erosion resistance**

- **Optimize high toughness erosion resistant turbine coatings**
- **Improve turbine airfoil TBCs with up to 3x erosion resistance**
- **Emphasize creep, fatigue, erosion, and CMAS interactions**
- **Develop multilayered damping and erosion coatings**
- **Develop turbine blade TBC life prediction model**

Future Directions for Low Conductivity TBC Development

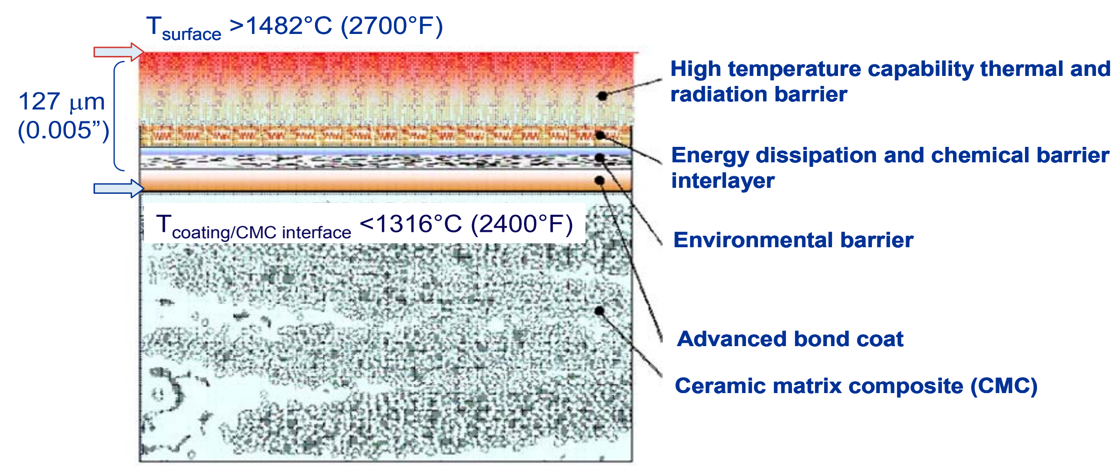
— **Emphasize thin ceramic matrix composite turbine coating processing**

- **Advanced processing for integrated TEBCs**

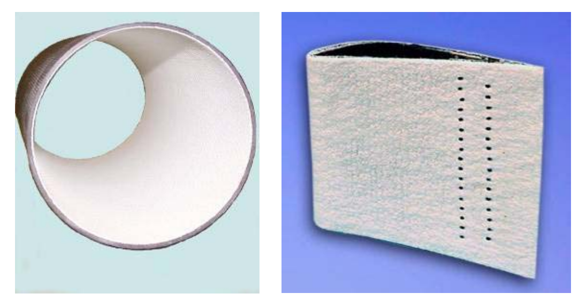
- **Ceramic nanocomposite and nanotube-based TEBCs for improved durability and optical properties**

- **Embedded sensors**

- **Life prediction methodology and design tool development**



CMC Turbine Blade coatings



CMC combustor liner and vane

Summary

- **Four-component low k TBC systems developed for low k combustor applications**

- **Advanced turbine airfoil TBCs being developed with combined low conductivity and high toughness**

- **Improved erosion/impact resistance observed for the multi-component coating t' and t'/cubic nano-composite systems**

- **Coatings being optimized for cyclic life, thermal conductivity and erosion/impact and CMAS resistance**

- **High heat flux durability, multifunctional coatings and lifing models being emphasized in the current research programs**